



US009036928B2

(12) **United States Patent**  
**Venkataraman et al.**

(10) **Patent No.:** **US 9,036,928 B2**  
(45) **Date of Patent:** **\*May 19, 2015**

(54) **SYSTEMS AND METHODS FOR ENCODING STRUCTURED LIGHT FIELD IMAGE FILES**

(71) Applicant: **Pelican Imaging Corporation**, Santa Clara, CA (US)

(72) Inventors: **Kartik Venkataraman**, San Jose, CA (US); **Semyon Nisenzon**, Palo Alto, CA (US); **Dan Lelescu**, Morgan Hill, CA (US)

(73) Assignee: **PELICAN IMAGING CORPORATION**, Santa Clara, CA (US)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/477,396**

(22) Filed: **Sep. 4, 2014**

(65) **Prior Publication Data**

US 2014/0369612 A1 Dec. 18, 2014

**Related U.S. Application Data**

(63) Continuation of application No. 13/631,731, filed on Sep. 28, 2012.

(60) Provisional application No. 61/540,188, filed on Sep. 28, 2011.

(51) **Int. Cl.**  
**G06K 9/36** (2006.01)  
**G06T 9/00** (2006.01)

(Continued)

(52) **U.S. Cl.**  
CPC ..... **H04N 13/0048** (2013.01); **G06K 9/36** (2013.01); **G06T 9/00** (2013.01); **G06T 9/20** (2013.01);

(Continued)

(58) **Field of Classification Search**  
USPC ..... 382/232, 154, 233, 235, 250, 284  
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,124,798 A 11/1978 Thompson  
4,198,646 A 4/1980 Alexander et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP 840502 A2 5/1998  
EP 2336816 A2 6/2011

(Continued)

OTHER PUBLICATIONS

International Search Report and Written Opinion for International Application No. PCT/US13/46002, Search Completed Nov. 13, 2013, Mailed Nov. 29, 2013, 7 pgs.

(Continued)

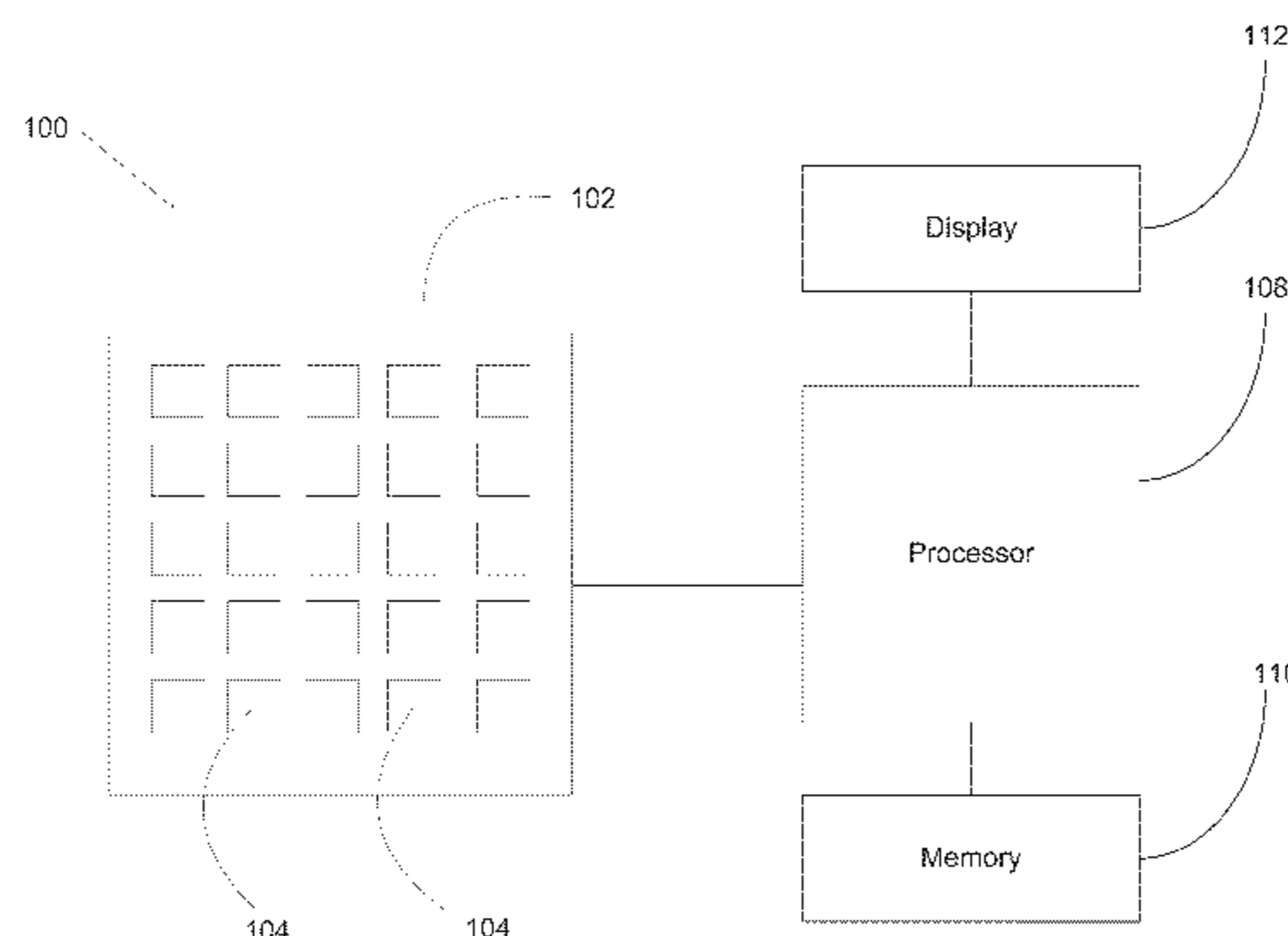
*Primary Examiner* — Duy M Dang

(74) *Attorney, Agent, or Firm* — KPPB LLP

(57) **ABSTRACT**

Systems and methods configured to store images synthesized from light field image data and metadata describing the images in electronic files and render images using the stored image and the metadata in accordance with embodiments of the invention are disclosed. One embodiment includes a processor and memory containing an encoding application and light field image data, where the light field image data comprises a plurality of low resolution images of a scene captured from different viewpoints. In addition, the encoding application configures the processor to: synthesize a higher resolution image of the scene from a reference viewpoint using the low resolution images, where synthesizing the higher resolution image involves creating a depth map that specifies depths from the reference viewpoint for pixels in the higher resolution image; encode the higher resolution image; and create a light field image file including the encoded image and metadata including the depth map.

**20 Claims, 19 Drawing Sheets**



(51)	<b>Int. Cl.</b>		8,131,097 B2	3/2012	Lelescu et al.
	<i>H04N 13/00</i>	(2006.01)	8,180,145 B2	5/2012	Wu et al.
	<i>G06T 9/20</i>	(2006.01)	8,189,089 B1	5/2012	Georgiev
	<i>H04N 19/597</i>	(2014.01)	8,212,914 B2	7/2012	Chiu
	<i>H04N 13/02</i>	(2006.01)	8,213,711 B2	7/2012	Tam
	<i>H04N 19/625</i>	(2014.01)	8,231,814 B2	7/2012	Duparre
			8,242,426 B2	8/2012	Ward et al.
			8,289,409 B2	10/2012	Chang
(52)	<b>U.S. Cl.</b>		8,294,099 B2	10/2012	Blackwell, Jr.
	CPC .....	<i>H04N 19/597</i> (2013.01); <i>H04N 13/0022</i>	8,305,456 B1	11/2012	McMahon
		(2013.01); <i>H04N 2013/0081</i> (2013.01); <i>H04N</i>	8,315,476 B1	11/2012	Georgiev et al.
		<i>13/0242</i> (2013.01); <i>H04N 13/0271</i> (2013.01);	8,345,144 B1	1/2013	Georgiev et al.
		<i>H04N 19/625</i> (2014.01)	8,360,574 B2	1/2013	Ishak et al.
			8,406,562 B2	3/2013	Bassi et al.
			8,446,492 B2	5/2013	Nakano et al.
			8,514,491 B2	8/2013	Duparre
(56)	<b>References Cited</b>		8,541,730 B2	9/2013	Inuiya
	<b>U.S. PATENT DOCUMENTS</b>		8,542,933 B2	9/2013	Venkataraman et al.
			8,619,082 B1	12/2013	Ciurea et al.
			8,692,893 B2	4/2014	McMahon
	4,323,925 A	4/1982 Abell et al.	8,780,113 B1	7/2014	Ciurea et al.
	4,460,449 A	7/1984 Montalbano	8,804,255 B2	8/2014	Duparre
	4,467,365 A	8/1984 Murayama et al.	8,831,367 B2	9/2014	Venkataraman et al.
	5,005,083 A	4/1991 Grage	8,861,089 B2	10/2014	Duparre
	5,070,414 A	12/1991 Tsutsumi	2001/0005225 A1	6/2001	Clark et al.
	5,144,448 A	9/1992 Hornbaker	2001/0038387 A1	11/2001	Tomooka et al.
	5,629,524 A	5/1997 Stettner et al.	2002/0012056 A1	1/2002	Trevino
	5,808,350 A	9/1998 Jack et al.	2002/0027608 A1	3/2002	Johnson et al.
	5,832,312 A	11/1998 Rieger et al.	2002/0063807 A1	5/2002	Margulis
	5,880,691 A	3/1999 Fossum et al.	2002/0087403 A1	7/2002	Meyers et al.
	5,933,190 A	8/1999 Dierickx et al.	2002/0089596 A1	7/2002	Yasuo
	5,973,844 A	10/1999 Burger	2002/0094027 A1	7/2002	Sato et al.
	6,002,743 A	12/1999 Telymonde	2002/0101528 A1	8/2002	Lee
	6,005,607 A	12/1999 Uomori et al.	2002/0113867 A1	8/2002	Takigawa et al.
	6,034,690 A	3/2000 Gallery et al.	2002/0113888 A1	8/2002	Sonoda et al.
	6,069,351 A	5/2000 Mack	2002/0163054 A1	11/2002	Suda et al.
	6,069,365 A	5/2000 Chow et al.	2002/0167537 A1	11/2002	Trajkovic
	6,097,394 A	8/2000 Levoy et al.	2002/0177054 A1	11/2002	Saitoh et al.
	6,124,974 A	9/2000 Burger	2003/0086079 A1	5/2003	Barth et al.
	6,137,535 A	10/2000 Meyers	2003/0124763 A1	7/2003	Fan et al.
	6,141,048 A	10/2000 Meyers	2003/0140347 A1	7/2003	Varsa
	6,175,379 B1	1/2001 Uomori et al.	2003/0179418 A1	9/2003	Wengender et al.
	6,239,909 B1	5/2001 Hayashi et al.	2003/0211405 A1	11/2003	Venkataraman
	6,358,862 B1	3/2002 Ireland et al.	2004/0008271 A1	1/2004	Hagimori et al.
	6,525,302 B2	2/2003 Dowski, Jr. et al.	2004/0012689 A1	1/2004	Tinnerino
	6,603,513 B1	8/2003 Berezin	2004/0047274 A1	3/2004	Amanai
	6,611,289 B1	8/2003 Yu	2004/0050104 A1	3/2004	Ghosh et al.
	6,627,896 B1	9/2003 Hashimoto et al.	2004/0056966 A1	3/2004	Schechner et al.
	6,635,941 B2	10/2003 Suda	2004/0100570 A1	5/2004	Shizukuishi
	6,671,399 B1	12/2003 Berestov	2004/0114807 A1	6/2004	Lelescu et al.
	6,750,904 B1	6/2004 Lambert	2004/0165090 A1	8/2004	Ning
	6,765,617 B1	7/2004 Tangen et al.	2004/0169617 A1	9/2004	Yelton et al.
	6,771,833 B1	8/2004 Edgar	2004/0170340 A1	9/2004	Tipping et al.
	6,774,941 B1	8/2004 Boisvert et al.	2004/0174439 A1	9/2004	Upton
	6,879,735 B1	4/2005 Portniaguine et al.	2004/0207836 A1	10/2004	Chhibber et al.
	6,903,770 B1	6/2005 Kobayashi et al.	2004/0213449 A1	10/2004	Safae-Rad et al.
	6,909,121 B2	6/2005 Nishikawa	2004/0234873 A1	11/2004	Venkataraman
	6,958,862 B1	10/2005 Joseph et al.	2004/0251509 A1	12/2004	Choi
	7,085,409 B2	8/2006 Sawhney et al.	2005/0006477 A1	1/2005	Patel
	7,199,348 B2	4/2007 Olsen et al.	2005/0012035 A1	1/2005	Miller
	7,262,799 B2	8/2007 Suda	2005/0036778 A1	2/2005	DeMonte
	7,292,735 B2	11/2007 Blake et al.	2005/0048690 A1	3/2005	Yamamoto
	7,295,697 B1	11/2007 Satoh	2005/0068436 A1	3/2005	Fraenkel et al.
	7,369,165 B2	5/2008 Bosco et al.	2005/0132098 A1	6/2005	Sonoda et al.
	7,391,572 B2	6/2008 Jacobowitz et al.	2005/0134712 A1	6/2005	Gruhlke et al.
	7,606,484 B1	10/2009 Richards et al.	2005/0151759 A1	7/2005	Gonzalez-Banos et al.
	7,633,511 B2	12/2009 Shum et al.	2005/0205785 A1	9/2005	Hornback et al.
	7,657,090 B2	2/2010 Omatsu et al.	2005/0219363 A1	10/2005	Kohler et al.
	7,675,080 B2	3/2010 Boettiger	2005/0225654 A1	10/2005	Feldman et al.
	7,675,681 B2	3/2010 Tomikawa et al.	2005/0286612 A1	12/2005	Takanashi
	7,706,634 B2	4/2010 Schmitt et al.	2006/0002635 A1	1/2006	Nestares et al.
	7,723,662 B2	5/2010 Levoy et al.	2006/0023197 A1	2/2006	Joel
	7,986,018 B2	7/2011 Rennie	2006/0023314 A1	2/2006	Boettiger et al.
	7,990,447 B2	8/2011 Honda et al.	2006/0033005 A1	2/2006	Jerdev et al.
	8,013,904 B2	9/2011 Tan et al.	2006/0034003 A1	2/2006	Zalevsky
	8,027,531 B2	9/2011 Wilburn et al.	2006/0038891 A1	2/2006	Okutomi et al.
	8,044,994 B2	10/2011 Vetro et al.	2006/0049930 A1	3/2006	Zruya et al.
	8,077,245 B2	12/2011 Adamo et al.	2006/0054780 A1	3/2006	Garrod et al.
	8,106,949 B2	1/2012 Tan et al.	2006/0054782 A1	3/2006	Olsen et al.
	8,126,279 B2	2/2012 Marcellin et al.			



(56)

## References Cited

## U.S. PATENT DOCUMENTS

2006/0072029	A1	4/2006	Miyatake et al.	2009/0201371	A1	8/2009	Matsuda et al.
2006/0087747	A1	4/2006	Ohzawa et al.	2009/0207235	A1	8/2009	Francini et al.
2006/0098888	A1	5/2006	Morishita	2009/0225203	A1	9/2009	Tanida et al.
2006/0125936	A1	6/2006	Gruhike et al.	2009/0237520	A1	9/2009	Kaneko et al.
2006/0138322	A1	6/2006	Costello et al.	2009/0268192	A1	10/2009	Koenck et al.
2006/0159369	A1	7/2006	Young	2009/0268983	A1	10/2009	Stone
2006/0176566	A1	8/2006	Boettiger et al.	2009/0274387	A1	11/2009	Jin
2006/0187338	A1	8/2006	May et al.	2009/0284651	A1	11/2009	Srinivasan
2006/0197937	A1	9/2006	Bamji et al.	2009/0297056	A1	12/2009	Lelescu et al.
2006/0210186	A1	9/2006	Berkner	2009/0302205	A9	12/2009	Olsen et al.
2006/0243889	A1	11/2006	Farnworth et al.	2009/0323195	A1	12/2009	Hembree et al.
2006/0251410	A1	11/2006	Trutna	2009/0323206	A1	12/2009	Oliver et al.
2006/0274174	A1	12/2006	Tewinkle	2009/0324118	A1	12/2009	Maslov et al.
2006/0278948	A1	12/2006	Yamaguchi et al.	2010/0002126	A1	1/2010	Wenstrand et al.
2006/0279648	A1	12/2006	Senba et al.	2010/0002313	A1	1/2010	Duparre et al.
2007/0002159	A1	1/2007	Olsen et al.	2010/0002314	A1	1/2010	Duparre
2007/0024614	A1	2/2007	Tam	2010/0053342	A1	3/2010	Hwang et al.
2007/0040828	A1	2/2007	Zalevsky et al.	2010/0053600	A1	3/2010	Tanida et al.
2007/0040922	A1	2/2007	McKee et al.	2010/0060746	A9	3/2010	Olsen et al.
2007/0041391	A1	2/2007	Lin et al.	2010/0086227	A1	4/2010	Sun et al.
2007/0052825	A1	3/2007	Cho	2010/0097491	A1	4/2010	Farina et al.
2007/0083114	A1	4/2007	Yang et al.	2010/0103259	A1	4/2010	Tanida et al.
2007/0085917	A1	4/2007	Kobayashi	2010/0103308	A1	4/2010	Butterfield et al.
2007/0102622	A1	5/2007	Olsen et al.	2010/0118127	A1	5/2010	Nam et al.
2007/0126898	A1	6/2007	Feldman	2010/0133418	A1	6/2010	Sargent et al.
2007/0127831	A1	6/2007	Venkataraman	2010/0141802	A1	6/2010	Knight et al.
2007/0139333	A1	6/2007	Sato et al.	2010/0142839	A1	6/2010	Lakus-Becker
2007/0146511	A1	6/2007	Kinoshita et al.	2010/0157073	A1	6/2010	Kondo et al.
2007/0159541	A1	7/2007	Sparks et al.	2010/0177411	A1	7/2010	Hegde et al.
2007/0160310	A1	7/2007	Tanida et al.	2010/0195716	A1	8/2010	Klein et al.
2007/0171290	A1	7/2007	Kroger	2010/0201834	A1	8/2010	Maruyama et al.
2007/0206241	A1	9/2007	Smith et al.	2010/0208100	A9	8/2010	Olsen et al.
2007/0211164	A1	9/2007	Olsen et al.	2010/0220212	A1	9/2010	Perlman et al.
2007/0216765	A1	9/2007	Wong et al.	2010/0231285	A1	9/2010	Boomer et al.
2007/0228256	A1	10/2007	Mentzer	2010/0244165	A1	9/2010	Lake et al.
2007/0257184	A1	11/2007	Olsen et al.	2010/0265385	A1	10/2010	Knight et al.
2007/0258006	A1	11/2007	Olsen et al.	2010/0281070	A1	11/2010	Chan et al.
2007/0258706	A1	11/2007	Raskar et al.	2010/0302423	A1	12/2010	Adams, Jr. et al.
2007/0268374	A1	11/2007	Robinson	2011/0001037	A1	1/2011	Tewinkle
2007/0296835	A1	12/2007	Olsen et al.	2011/0032370	A1	2/2011	Ludwig
2008/0019611	A1	1/2008	Larkin	2011/0043661	A1	2/2011	Podoleanu
2008/0025649	A1	1/2008	Liu et al.	2011/0043665	A1	2/2011	Ogasahara
2008/0030597	A1	2/2008	Olsen et al.	2011/0043668	A1	2/2011	McKinnon et al.
2008/0043095	A1	2/2008	Vetro et al.	2011/0069189	A1	3/2011	Venkataraman et al.
2008/0043096	A1	2/2008	Vetro et al.	2011/0080487	A1	4/2011	Venkataraman et al.
2008/0080028	A1	4/2008	Bakin et al.	2011/0108708	A1	5/2011	Olsen et al.
2008/0084486	A1	4/2008	Enge et al.	2011/0121421	A1	5/2011	Charbon et al.
2008/0088793	A1	4/2008	Sverdrup et al.	2011/0122308	A1	5/2011	Duparre
2008/0118241	A1	5/2008	Tekolste et al.	2011/0153248	A1	6/2011	Gu et al.
2008/0131019	A1	6/2008	Ng	2011/0211824	A1	9/2011	Georgiev et al.
2008/0131107	A1	6/2008	Ueno	2011/0221658	A1	9/2011	Haddick et al.
2008/0151097	A1	6/2008	Chen et al.	2011/0241234	A1	10/2011	Duparre
2008/0152215	A1	6/2008	Horie et al.	2011/0242342	A1	10/2011	Goma et al.
2008/0152296	A1	6/2008	Oh et al.	2011/0242355	A1	10/2011	Goma et al.
2008/0158698	A1	7/2008	Chang et al.	2011/0242356	A1	10/2011	Aleksic et al.
2008/0193026	A1	8/2008	Horie et al.	2011/0255592	A1	10/2011	Sung et al.
2008/0218610	A1	9/2008	Chapman et al.	2011/0255745	A1	10/2011	Hodder et al.
2008/0219654	A1	9/2008	Border et al.	2011/0267348	A1	11/2011	Lin et al.
2008/0239116	A1	10/2008	Smith	2011/0273531	A1	11/2011	Ito et al.
2008/0247638	A1	10/2008	Tanida et al.	2011/0274366	A1	11/2011	Tardif
2008/0247653	A1	10/2008	Moussavi et al.	2011/0279721	A1	11/2011	McMahon
2008/0278591	A1	11/2008	Barna et al.	2011/0285866	A1	11/2011	Bhrugumalla et al.
2009/0050946	A1	2/2009	Duparre et al.	2011/0300929	A1	12/2011	Tardif et al.
2009/0052743	A1	2/2009	Techmer	2011/0310980	A1	12/2011	Mathew
2009/0060281	A1	3/2009	Tanida et al.	2011/0317766	A1	12/2011	Lim, II et al.
2009/0086074	A1	4/2009	Li et al.	2012/0012748	A1	1/2012	Pain et al.
2009/0091806	A1	4/2009	Inuiya	2012/0026342	A1	2/2012	Yu et al.
2009/0102956	A1	4/2009	Georgiev	2012/0039525	A1	2/2012	Tian et al.
2009/0109306	A1	4/2009	Shan et al.	2012/0044372	A1	2/2012	Côté et al.
2009/0128833	A1	5/2009	Yahav	2012/0069235	A1	3/2012	Imai
2009/0152664	A1	6/2009	Klem et al.	2012/0105691	A1	5/2012	Waqas et al.
2009/0167922	A1	7/2009	Perlman et al.	2012/0113413	A1	5/2012	Miahczylowicz-Wolski et al.
2009/0179142	A1	7/2009	Duparre et al.	2012/0147205	A1	6/2012	Lelescu et al.
2009/0180021	A1	7/2009	Kikuchi et al.	2012/0188634	A1	7/2012	Kubala et al.
2009/0200622	A1	8/2009	Tai et al.	2012/0198677	A1	8/2012	Duparre
				2012/0200734	A1	8/2012	Tang
				2012/0249550	A1	10/2012	Akeley et al.
				2012/0262607	A1	10/2012	Shimura et al.
				2012/0287291	A1	11/2012	McMahon



(56)

**References Cited**

## U.S. PATENT DOCUMENTS

2012/0293695 A1 11/2012 Tanaka  
 2012/0314033 A1 12/2012 Lee, III et al.  
 2012/0327222 A1 12/2012 Ng et al.  
 2013/0003184 A1 1/2013 Duparre  
 2013/0010073 A1 1/2013 Do  
 2013/0022111 A1 1/2013 Chen et al.  
 2013/0027580 A1 1/2013 Olsen et al.  
 2013/0033579 A1 2/2013 Wajs  
 2013/0050504 A1 2/2013 Safaee-Rad et al.  
 2013/0050526 A1 2/2013 Keelan  
 2013/0057710 A1 3/2013 McMahon  
 2013/0070060 A1 3/2013 Chatterjee  
 2013/0077880 A1 3/2013 Venkataraman et al.  
 2013/0077882 A1 3/2013 Venkataraman et al.  
 2013/0088637 A1 4/2013 Duparre  
 2013/0120605 A1 5/2013 Georgiev et al.  
 2013/0128068 A1 5/2013 Georgiev et al.  
 2013/0128069 A1 5/2013 Georgiev et al.  
 2013/0128087 A1 5/2013 Georgiev et al.  
 2013/0147979 A1 6/2013 McMahon et al.  
 2013/0215108 A1 8/2013 McMahon et al.  
 2013/0259317 A1 10/2013 Gaddy  
 2013/0265459 A1 10/2013 Duparre et al.  
 2014/0104490 A1 4/2014 Hsieh et al.  
 2014/0118493 A1 5/2014 Sali et al.  
 2014/0132810 A1 5/2014 McMahon  
 2014/0192253 A1 7/2014 Laroia  
 2014/0218546 A1 8/2014 McMahan  
 2014/0232822 A1 8/2014 Venkataraman et al.  
 2014/0240528 A1 8/2014 Venkataraman et al.  
 2014/0240529 A1 8/2014 Venkataraman et al.  
 2014/0267243 A1 9/2014 Venkataraman et al.  
 2014/0267633 A1 9/2014 Venkataraman et al.  
 2014/0267762 A1 9/2014 Mullis et al.  
 2014/0267890 A1 9/2014 Lelescu et al.  
 2015/0036014 A1 2/2015 Lelescu et al.  
 2015/0036015 A1 2/2015 Lelescu et al.  
 2015/0042766 A1 2/2015 Ciurea et al.  
 2015/0042767 A1 2/2015 Ciurea et al.  
 2015/0042833 A1 2/2015 Lelescu et al.  
 2015/0049915 A1 2/2015 Ciurea et al.  
 2015/0049916 A1 2/2015 Ciurea et al.  
 2015/0049917 A1 2/2015 Ciurea et al.  
 2015/0055884 A1 2/2015 Venkataraman et al.

## FOREIGN PATENT DOCUMENTS

JP 2006033493 A 2/2006  
 JP 2007520107 A 7/2007  
 JP 2011109484 A 6/2011  
 WO 2007083579 A1 7/2007  
 WO 2008108271 A1 9/2008  
 WO 2009151903 A2 12/2009  
 WO 2011063347 A2 5/2011  
 WO 2011116203 A1 9/2011  
 WO 2011063347 A3 10/2011  
 WO 2011143501 A1 11/2011  
 WO 2012057619 A1 5/2012  
 WO 2012057620 A2 5/2012  
 WO 2012057622 A1 5/2012  
 WO 2012057623 A1 5/2012  
 WO 2012057620 A3 6/2012  
 WO 2012074361 A1 6/2012  
 WO 2012078126 A1 6/2012  
 WO 2012082904 A1 6/2012  
 WO 2012155119 A1 11/2012  
 WO 2013003276 A1 1/2013  
 WO 2013043751 A1 3/2013  
 WO 2013043761 A1 3/2013  
 WO 2013049699 A1 4/2013  
 WO 2013055960 A1 4/2013  
 WO 2013119706 A1 8/2013  
 WO 2013126578 A1 8/2013  
 WO 2014052974 A2 4/2014

WO 2012057621 A1 5/2014  
 WO 2014032020 A3 5/2014  
 WO 2014078443 A1 5/2014  
 WO 2014130849 A1 8/2014  
 WO 2014133974 A1 9/2014  
 WO 2014138695 A1 9/2014  
 WO 2014138697 A1 9/2014  
 WO 2014145856 A1 9/2014  
 WO 2014149403 A1 9/2014  
 WO 2014150856 A1 9/2014

## OTHER PUBLICATIONS

International Search Report and Written Opinion for International Application No. PCT/US13/48772, Search Completed Oct. 21, 2013, Mailed Nov. 8, 2013, 6 pgs.  
 International Search Report and Written Opinion for International Application No. PCT/US13/56065, Search Completed Nov. 25, 2013, Mailed Nov. 26, 2013, 8 pgs.  
 International Search Report and Written Opinion for International Application No. PCT/US13/59991, Search Completed Feb. 6, 2014, Mailed Feb. 26, 2014, 8 pgs.  
 International Search Report and Written Opinion for International Application No. PCT/US2009/044687, date completed Jan. 5, 2010, date mailed Jan. 13, 2010, 9 pgs.  
 International Search Report and Written Opinion for International Application No. PCT/US2013/024987, Search Completed Mar. 27, 2013, Mailed Apr. 15, 2013, 14 pgs.  
 International Search Report and Written Opinion for International Application No. PCT/US2013/056502, Search Completed Feb. 18, 2014, Mailed Mar. 19, 2014, 7 pgs.  
 International Search Report and Written Opinion for International Application No. PCT/US2013/069932, International Filing Date Nov. 13, 2013, Search Completed Mar. 14, 2014, Mailed Apr. 14, 2014, 12 pgs.  
 International Search Report and Written Opinion for International Application PCT/US13/62720, report completed Mar. 25, 2014, Mailed Apr. 21, 2014, 9 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/024903 report completed Jun. 12, 2014, Mailed, Jun. 27, 2014, 13 pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/17766, report completed May 28, 2014, Mailed Jun. 18, 2014, 9 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/18084, report completed May 23, 2014, Mailed Jun. 10, 2014, 12 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/18116, report completed May 13, 2014, Mailed Jun. 2, 2014, 12 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/24407, report completed Jun. 11, 2014, Mailed Jul. 8, 2014, 9 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/25100, report completed Jul. 7, 2014, Mailed Aug. 7, 2014 5 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US14/25904 report completed Jun. 10, 2014, Mailed Jul. 10, 2014, 6 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US2014/022123, report completed Jun. 9, 2014, Mailed Jun. 25, 2014, 5 pgs.  
 International Search Report and Written Opinion for International Application PCT/US2014/024947, Report Completed Jul. 8, 2014, Mailed Aug. 5, 2014, 8 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US2014/028447, report completed Jun. 30, 2014, Mailed Jul. 21, 2014, 8 Pgs.  
 International Search Report and Written Opinion for International Application PCT/US2014/23762, Report Completed May 30, 2014, Mailed Jul. 3, 2014, 6 Pgs.  
 IPRP for International Application No. PCT/US2012/059813, International Filing Date Oct. 11, 2012, Search Completed Apr. 15, 2014, 7 pgs.



(56)

**References Cited**

## OTHER PUBLICATIONS

Search Report and Written Opinion for International Application PCT/US11/36349, mailed Aug. 22, 2011, 12 pgs.

International Preliminary Report on Patentability for International Application PCT/US2013/024987, Mailed Aug. 21, 2014, 13 Pgs., Aug. 21, 2014.

International Search Report and Written Opinion for International Application PCT/US2014/030692, report completed Jul. 28, 2014, Mailed Aug. 27, 2014, 7 Pages.

International Search Report and Written Opinion for International Application No. PCT/US2011/64921, Report Completed Feb. 25, 2011, mailed Mar. 6, 2012, 17 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2013/027146, completed Apr. 2, 2013, 12 pgs.

International Search Report and Written Opinion for International Application PCT/US14/22118, report completed Jun. 9, 2014, Mailed, Jun. 25, 2014, 5 pgs.

International Search Report and Written Opinion for International Application PCT/US2010/057661, completed Mar. 9, 2011, 14 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/044014, completed Oct. 12, 2012, 15 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/056151, completed Nov. 14, 2012, 10 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/059813, completed Dec. 17, 2012, 8 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/37670, Mailed Jul. 18, 2012, Search Completed Jul. 5, 2012, 9 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/58093, completed Nov. 15, 2012, 12 pgs. Office Action for U.S. Appl. No. 12/952,106, dated Aug. 16, 2012, 12 pgs.

Baker et al., "Limits on Super-Resolution and How to Break Them", IEEE Transactions on Pattern Analysis and Machine Intelligence, Sep. 2002, vol. 24, No. 9, pp. 1167-1183.

Bertero et al., "Super-resolution in computational imaging", Micron, 2003, vol. 34, Issues 6-7, 17 pgs.

Bishop et al., "Full-Resolution Depth Map Estimation from an Aliased Plenoptic Light Field", ACCV 2010, Part II, LNCS 6493, pp. 186-200.

Bishop et al., "The Light Field Camera: Extended Depth of Field, Aliasing, and Superresolution", IEEE Transactions on Pattern Analysis and Machine Intelligence, May 2012, vol. 34, No. 5, pp. 972-986.

Borman, "Topics in Multiframe Superresolution Restoration", Thesis of Sean Borman, Apr. 2004, 282 pgs.

Borman et al., "Image Sequence Processing", Source unknown, Oct. 14, 2002, 81 pgs.

Borman et al., "Block-Matching Sub-Pixel Motion Estimation from Noisy, Under-Sampled Frames—An Empirical Performance Evaluation", Proc SPIE, Dec. 1998, 3653, 10 pgs.

Borman et al., "Image Resampling and Constraint Formulation for Multi-Frame Super-Resolution Restoration", Proc. SPIE, Jun. 2003, 5016, 12 pgs.

Borman et al., "Linear models for multi-frame super-resolution restoration under non-affine registration and spatially varying PSF", Proc. SPIE, May 2004, vol. 5299, 12 pgs.

Borman et al., "Nonlinear Prediction Methods for Estimation of Clique Weighting Parameters in NonGaussian Image Models", Proc. SPIE, 1998, 3459, 9 pgs.

Borman et al., "Simultaneous Multi-Frame MAP Super-Resolution Video Enhancement Using Spatio-Temporal Priors", Image Processing, 1999, ICIP 99 Proceedings, vol. 3, pp. 469-473.

Borman et al., "Super-Resolution from Image Sequences—A Review", Circuits & Systems, 1998, pp. 374-378.

Bruckner et al., "Artificial compound eye applying hyperacuity", Optics Express, Dec. 11, 2006, vol. 14, No. 25, pp. 12076-12084.

Bruckner et al., "Driving microoptical imaging systems towards miniature camera applications", Proc. SPIE, Micro-Optics, 2010, 11 pgs.

Bruckner et al., "Thin wafer-level camera lenses inspired by insect compound eyes", Optics Express, Nov. 22, 2010, vol. 18, No. 24, pp. 24379-24394.

Capel, "Image Mosaicing and Super-resolution", [online], Retrieved on Nov. 10, 2012. Retrieved from the Internet at URL:<<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.226.2643&rep=rep1&type=pdf>>, Title pg., abstract, table of contents, pp. 1-263 (269 total pages).

Chan et al., "Extending the Depth of Field in a Compound-Eye Imaging System with Super-Resolution Reconstruction", Proceedings—International Conference on Pattern Recognition, 2006, vol. 3, pp. 623-626.

Chan et al., "Investigation of Computational Compound-Eye Imaging System with Super-Resolution Reconstruction", IEEE, ISASSP 2006, pp. 1177-1180.

Chan et al., "Super-resolution reconstruction in a computational compound-eye imaging system", Multidim. Syst. Sign Process, 2007, vol. 18, pp. 83-101.

Chen et al., "Interactive deformation of light fields", In Proceedings of Siggraph I3D 2005, pp. 139-146.

Drouin et al., "Fast Multiple-Baseline Stereo with Occlusion", Proceedings of The Fifth International Conference on 3-D Digital Imaging and Modeling, 2005, 8 pgs.

Drouin et al., "Geo-Consistency for Wide Multi-Camera Stereo", Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2005, 8 pgs.

Drouin et al., "Improving Border Localization of Multi-Baseline Stereo Using Border-Cut", International Journal of Computer Vision, Jul. 2009, vol. 83, Issue 3, 8 pgs.

Duparre et al., "Artificial apposition compound eye fabricated by micro-optics technology", Applied Optics, Aug. 1, 2004, vol. 43, No. 22, pp. 4303-4310.

Duparre et al., "Artificial compound eye zoom camera", Bioinspiration & Biomimetics, 2008, vol. 3, pp. 1-6.

Duparre et al., "Artificial compound eyes—different concepts and their application to ultra flat image acquisition sensors", MOEMS and Miniaturized Systems IV, Proc. SPIE 5346, Jan. 2004, pp. 89-100.

Duparre et al., "Chirped arrays of refractive ellipsoidal microlenses for aberration correction under oblique incidence", Optics Express, Dec. 26, 2005, vol. 13, No. 26, pp. 10539-10551.

Duparre et al., "Micro-optical artificial compound eyes", Bioinspiration & Biomimetics, 2006, vol. 1, pp. R1-R16.

Duparre et al., "Microoptical artificial compound eyes—from design to experimental verification of two different concepts", Proc. of SPIE, Optical Design and Engineering II, vol. 5962, pp. 59622A-1-59622A-12.

Duparre et al., "Microoptical Artificial Compound Eyes—Two Different Concepts for Compact Imaging Systems", 11th Microoptics Conference, Oct. 30-Nov. 2, 2005, 2 pgs.

Duparre et al., "Microoptical telescope compound eye", Optics Express, Feb. 7, 2005, vol. 13, No. 3, pp. 889-903.

Duparre et al., "Micro-optically fabricated artificial apposition compound eye", Electronic Imaging—Science and Technology, Proc. SPIE 5301, Jan. 2004, pp. 25-33.

Duparre et al., "Novel Optics/Micro-Optics for Miniature Imaging Systems", Proc. of SPIE, 2006, vol. 6196, pp. 619607-1-619607-15.

Duparre et al., "Theoretical analysis of an artificial superposition compound eye for application in ultra flat digital image acquisition devices", Optical Systems Design, Proc. SPIE 5249, Sep. 2003, pp. 408-418.

Duparre et al., "Thin compound-eye camera", Applied Optics, May 20, 2005, vol. 44, No. 15, pp. 2949-2956.

Duparre et al., "Ultra-Thin Camera Based on Artificial Apposition Compound Eyes", 10th Microoptics Conference, Sep. 1-3, 2004, 2 pgs.

Fanaswala, "Regularized Super-Resolution of Multi-View Images", Retrieved on Nov. 10, 2012. Retrieved from the Internet at URL:<[http://www.site.uottawa.ca/~edubois/theses/Fanaswala\\_thesis.pdf](http://www.site.uottawa.ca/~edubois/theses/Fanaswala_thesis.pdf)>, 163 pgs.

Farrell et al., "Resolution and Light Sensitivity Tradeoff with Pixel Size", Proceedings of the SPIE Electronic Imaging 2006 Conference, 2006, vol. 6069, 8 pgs.



(56)

## References Cited

## OTHER PUBLICATIONS

- Farsiu et al., "Advances and Challenges in Super-Resolution", *International Journal of Imaging Systems and Technology*, 2004, vol. 14, pp. 47-57.
- Farsiu et al., "Fast and Robust Multiframe Super Resolution", *IEEE Transactions on Image Processing*, Oct. 2004, vol. 13, No. 10, pp. 1327-1344.
- Farsiu et al., "Multiframe Demosaicing and Super-Resolution of Color Images", *IEEE Transactions on Image Processing*, Jan. 2006, vol. 15, No. 1, pp. 141-159.
- Feris et al., "Multi-Flash Stereopsis: Depth Edge Preserving Stereo with Small Baseline Illumination", *IEEE Trans on PAMI*, 2006, 31 pgs.
- Fife et al., "A 3D Multi-Aperture Image Sensor Architecture", *Custom Integrated Circuits Conference, 2006, CICC '06, IEEE*, pp. 281-284.
- Fife et al., "A 3MPixel Multi-Aperture Image Sensor with 0.7Mu Pixels in 0.11Mu CMOS", *ISSCC 2008, Session 2, Image Sensors & Technology*, 2008, pp. 48-50.
- Goldman et al., "Video Object Annotation, Navigation, and Composition", In *Proceedings of UIST 2008*, pp. 3-12.
- Gortler et al., "The Lumigraph", In *Proceedings of Siggraph 1996*, pp. 43-54.
- Hacohen et al., "Non-Rigid Dense Correspondence with Applications for Image Enhancement", *ACM Transactions on Graphics*, 30, 4, 2011, pp. 70:1-70:10.
- Hamilton, "JPEG File Interchange Format, Version 1.02", Sep. 1, 1992, 9 pgs.
- Hardie, "A Fast Image Super-Algorithm Using an Adaptive Wiener Filter", *IEEE Transactions on Image Processing*, Dec. 2007, vol. 16, No. 12, pp. 2953-2964.
- Hasinoff et al., "Search-and-Replace Editing for Personal Photo Collections", *Computational Photography (ICCP) 2010*, pp. 1-8.
- Horisaki et al., "Irregular Lens Arrangement Design to Improve Imaging Performance of Compound-Eye Imaging Systems", *Applied Physics Express*, 2010, vol. 3, pp. 022501-1-022501-3.
- Horisaki et al., "Superposition Imaging for Three-Dimensionally Space-Invariant Point Spread Functions", *Applied Physics Express*, 2011, vol. 4, pp. 112501-1-112501-3.
- Horn et al., "LightShop: Interactive Light Field Manipulation and Rendering", In *Proceedings of I3D 2007*, pp. 121-128.
- Isaksen et al., "Dynamically Reparameterized Light Fields", In *Proceedings of Siggraph 2000*, pp. 297-306.
- Jarabo et al., "Efficient Propagation of Light Field Edits", In *Proceedings of SIACG 2011*, pp. 75-80.
- Kang et al., "Handling Occlusions in Dense Multi-View Stereo", *Computer Vision and Pattern Recognition*, 2001, vol. 1, pp. 1-103-1-110.
- Kitamura et al., "Reconstruction of a high-resolution image on a compound-eye image-capturing system", *Applied Optics*, Mar. 10, 2004, vol. 43, No. 8, pp. 1719-1727.
- Krishnamurthy et al., "Compression and Transmission of Depth Maps for Image-Based Rendering", *Image Processing*, 2001, pp. 828-831.
- Kutulakos et al., "Occluding Contour Detection Using Affine Invariants and Purposive Viewpoint Control", *Proc., CVPR 94*, 8 pgs.
- Lensvector, "How LensVector Autofocus Works", printed Nov. 2, 2012 from <http://www.lensvector.com/overview.html>, 1 pg.
- Levoy, "Light Fields and Computational Imaging", *IEEE Computer Society*, Aug. 2006, pp. 46-55.
- Levoy et al., "Light Field Rendering", *Proc. ACM Siggraph '96*, pp. 1-12.
- Li et al., "A Hybrid Camera for Motion Deblurring and Depth Map Super-Resolution," Jun. 23-28, 2008, *IEEE Conference on Computer Vision and Pattern Recognition*, 8 pgs. Retrieved from [www.eecis.udel.edu/~jye/lab\\_research/08/deblur-feng.pdf](http://www.eecis.udel.edu/~jye/lab_research/08/deblur-feng.pdf) on Feb. 5, 2014.
- Liu et al., "Virtual View Reconstruction Using Temporal Information", *2012 IEEE International Conference on Multimedia and Expo*, 2012, pp. 115-120.
- Lo et al., "Stereoscopic 3D Copy & Paste", *ACM Transactions on Graphics*, vol. 29, No. 6, Article 147, Dec. 2010, pp. 147:1-147:10.
- Muehlebach, "Camera Auto Exposure Control for VSLAM Applications", *Studies on Mechatronics*, Swiss Federal Institute of Technology Zurich, Autumn Term 2010 course, 67 pgs.
- Nayar, "Computational Cameras: Redefining the Image", *IEEE Computer Society*, Aug. 2006, pp. 30-38.
- Joshi et al., "Synthetic Aperture Tracking: Tracking Through Occlusions", *I CCV IEEE 11th International Conference on Computer Vision; Publication [online]*. Oct. 2007 [retrieved Jul. 28, 2014]. Retrieved from the Internet: <URL:<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4409032&isnumber=4408819>>; pp. 1-8.
- Ng, "Digital Light Field Photography", Thesis, Jul. 2006, 203 pgs.
- Ng et al., "Super-Resolution Image Restoration from Blurred Low-Resolution Images", *Journal of Mathematical Imaging and Vision*, 2005, vol. 23, pp. 367-378.
- Nitta et al., "Image reconstruction for thin observation module by bound optics by using the iterative backprojection method", *Applied Optics*, May 1, 2006, vol. 45, No. 13, pp. 2893-2900.
- Nomura et al., "Scene Collages and Flexible Camera Arrays", *Proceedings of Eurographics Symposium on Rendering*, 2007, 12 pgs.
- Park et al., "Super-Resolution Image Reconstruction", *IEEE Signal Processing Magazine*, May 2003, pp. 21-36.
- Pham et al., "Robust Super-Resolution without Regularization", *Journal of Physics: Conference Series* 124, 2008, pp. 1-19.
- Protter et al., "Generalizing the Nonlocal-Means to Super-Resolution Reconstruction", *IEEE Transactions on Image Processing*, Jan. 2009, vol. 18, No. 1, pp. 36-51.
- Radtke et al., "Laser lithographic fabrication and characterization of a spherical artificial compound eye", *Optics Express*, Mar. 19, 2007, vol. 15, No. 6, pp. 3067-3077.
- Rander et al., "Virtualized Reality: Constructing Time-Varying Virtual Worlds From Real World Events", *Proc. of IEEE Visualization '97*, Phoenix, Arizona, Oct. 19-24, 1997, pp. 277-283, 552.
- Rhemann et al., "Fast Cost-Volume Filtering for Visual Correspondence and Beyond", *IEEE Trans. Pattern Anal. Mach. Intell.*, 2013, vol. 35, No. 2, pp. 504-511.
- Robertson et al., "Dynamic Range Improvement Through Multiple Exposures", In *Proc. of the Int. Conf. on Image Processing*, 1999, 5 pgs.
- Robertson et al., "Estimation-theoretic approach to dynamic range enhancement using multiple exposures", *Journal of Electronic Imaging*, Apr. 2003, vol. 12, No. 2, pp. 219-228.
- Roy et al., "Non-Uniform Hierarchical Pyramid Stereo for Large Images", *Computer and Robot Vision*, 2007, pp. 208-215.
- Sauer et al., "Parallel Computation of Sequential Pixel Updates in Statistical Tomographic Reconstruction", *ICIP 1995*, pp. 93-96.
- Shum et al., "Pop-Up Light Field: An Interactive Image-Based Modeling and Rendering System", *ACM Transactions on Graphics*, vol. 23, No. 2, Apr. 2004, pp. 143-162.
- Stollberg et al., "The Gabor superlens as an alternative wafer-level camera approach inspired by superposition compound eyes of nocturnal insects", *Optics Express*, Aug. 31, 2009, vol. 17, No. 18, pp. 15747-15759.
- Takeda et al., "Super-resolution Without Explicit Subpixel Motion Estimation", *IEEE Transaction on Image Processing*, Sep. 2009, vol. 18, No. 9, pp. 1958-1975.
- Tanida et al., "Color imaging with an integrated compound imaging system", *Optics Express*, Sep. 8, 2003, vol. 11, No. 18, pp. 2109-2117.
- Tanida et al., "Thin observation module by bound optics (TOMBO): concept and experimental verification", *Applied Optics*, Apr. 10, 2001, vol. 40, No. 11, pp. 1806-1813.
- Vaish et al., "Reconstructing Occluded Surfaces Using Synthetic Apertures: Stereo, Focus and Robust Measures", *Proceeding, CVPR '06 Proceedings of the 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition—vol. 2*, pp. 2331-2338.
- Vaish et al., "Synthetic Aperture Focusing Using a Shear-Warp Factorization of the Viewing Transform", *IEEE Workshop on A3DISS, CVPR*, 2005, 8 pgs.
- Vaish et al., "Using Plane + Parallax for Calibrating Dense Camera Arrays", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2004, 8 pgs.



(56)

**References Cited**

## OTHER PUBLICATIONS

Veilleux, "CCD Gain Lab: The Theory", University of Maryland, College Park-Observational Astronomy (ASTR 310), Oct. 19, 2006, pp. 1-5 (online), [retrieved on May 13, 2014]. Retrieved from the Internet <URL: [http://www.astro.umd.edu/~veilleux/ASTR310/fall06/ccd\\_theory.pdf](http://www.astro.umd.edu/~veilleux/ASTR310/fall06/ccd_theory.pdf), 5 pgs.

Vuong et al., "A New Auto Exposure and Auto White-Balance Algorithm to Detect High Dynamic Range Conditions Using CMOS Technology", Proceedings of the World Congress on Engineering and Computer Science 2008, WCECS 2008, Oct. 22-24, 2008.

Wetzstein et al., "Computational Plenoptic Imaging", Computer Graphics Forum, 2011, vol. 30, No. 8, pp. 2397-2426.

Wheeler et al., "Super-Resolution Image Synthesis Using Projections Onto Convex Sets in the Frequency Domain", Proc. SPIE, 2005, 5674, 12 pgs.

Wilburn, "High Performance Imaging Using Arrays of Inexpensive Cameras", Thesis of Bennett Wilburn, Dec. 2004, 128 pgs.

Wilburn et al., "High Performance Imaging Using Large Camera Arrays", ACM Transactions on Graphics, Jul. 2005, vol. 24, No. 3, pp. 765-776.

Wilburn et al., "High-Speed Videography Using a Dense Camera Array", Proceeding, CVPR'04 Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pp. 294-301.

Wilburn et al., "The Light Field Video Camera", Proceedings of Media Processors 2002, SPIE Electronic Imaging, 2002, 8 pgs.

Wippermann et al., "Design and fabrication of a chirped array of refractive ellipsoidal micro-lenses for an apposition eye camera objective", Proceedings of SPIE, Optical Design and Engineering II, Oct. 15, 2005, 59622C-1-59622C11.

Yang et al., "A Real-Time Distributed Light Field Camera", Eurographics Workshop on Rendering (2002), pp. 1-10.

Zhang et al., "A Self-Reconfigurable Camera Array", Eurographics Symposium on Rendering, 2004, 12 pgs.

Zomet et al., "Robust Super-Resolution", IEEE, 2001, pp. 1-6.

International Preliminary Report on Patentability for International Application PCT/US2013/027146, Report Completed Apr. 2, 2013, Mailed Sep. 4, 2014, 10 Pages.

Extended European Search Report for European Application EP12835041.0, Report Completed Jan. 28, 2015, Mailed Feb. 4, 2015, 6 Pgs.

International Preliminary Report on Patentability for International Application PCT/US2014/023762, Report Issued Mar. 2, 2015, Mailed Mar. 9, 2015, 19 Pgs.

International Preliminary Report on Patentability for International Application PCT/US13/56065, Report Issued Feb 24, 2015, Mailed Mar 5, 2015, 4 Pgs.

International Preliminary Report on Patentability for International Application PCT/US2013/056502, Report Issued Feb 24, 2015, Mailed Mar 5, 2015, 7 Pgs.

Chen et al., "KNN Matting", IEEE Transactions on Pattern Analysis and Machine Intelligence, Sep. 2013, vol. 35, No. 9, pp. 2175-2188.

Lai et al., "A Large-Scale Hierarchical Multi-View RGB-D Object Dataset", 8 pgs. Robotics and Automation (ICRA), 2011 IEEE International Conference on, May 2011.

Levin et al., "A Closed Form Solution to Natural Image Matting", Pattern Analysis and Machine Intelligence, Feb. 2008, vol. 30, 8 pgs.

Perwass et al., "Single Lens 3D-Camera with Extended Depth-of-Field", printed from [www.raytrix.de](http://www.raytrix.de), 15 pgs. SPIE Proceedings, vol. 8291, Feb. 9, 2012.

Tallon et al., "Upsampling and Denoising of Depth Maps Via Joint-Segmentation", 20th European Signal Processing Conference, Aug 27-31, 2012, 5 pgs.

Zhang, Qiang et al., "Depth estimation, spatially variant image registration, and super-resolution using a multi-lenslet camera", Proceedings of SPIE, vol. 7705, Apr. 23, 2010, pp. 770505-770505-8, XP055113797 ISSN: 0277-786X, DOI: 10.1117/12.852171.

US 8,957,977, 02/2015, Venkataraman et al. (withdrawn)

US 8,964,053, 02/2015, Venkataraman et al. (withdrawn)

US 8,965,058, 02/2015, Venkataraman et al. (withdrawn)

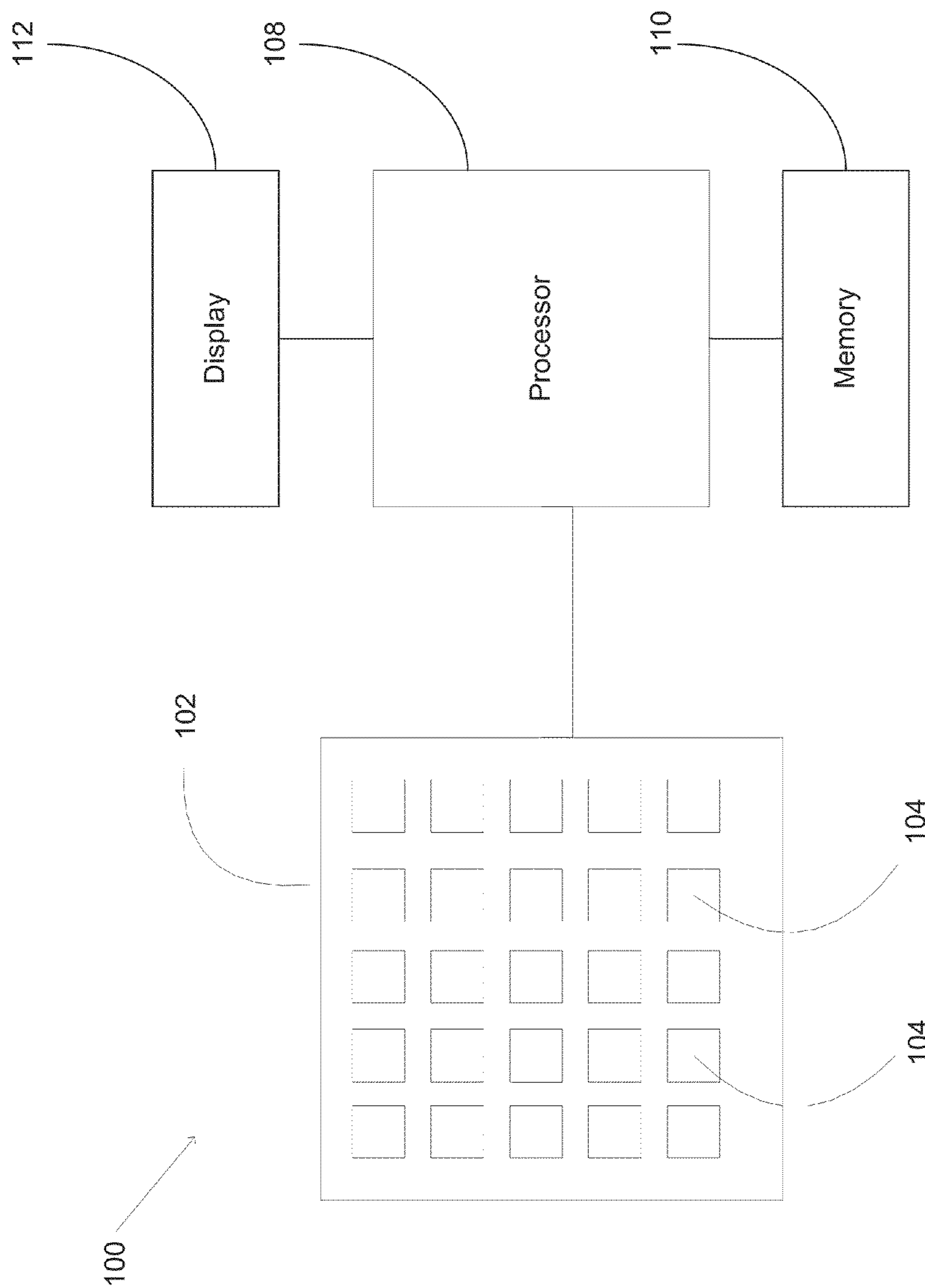


FIG. 1



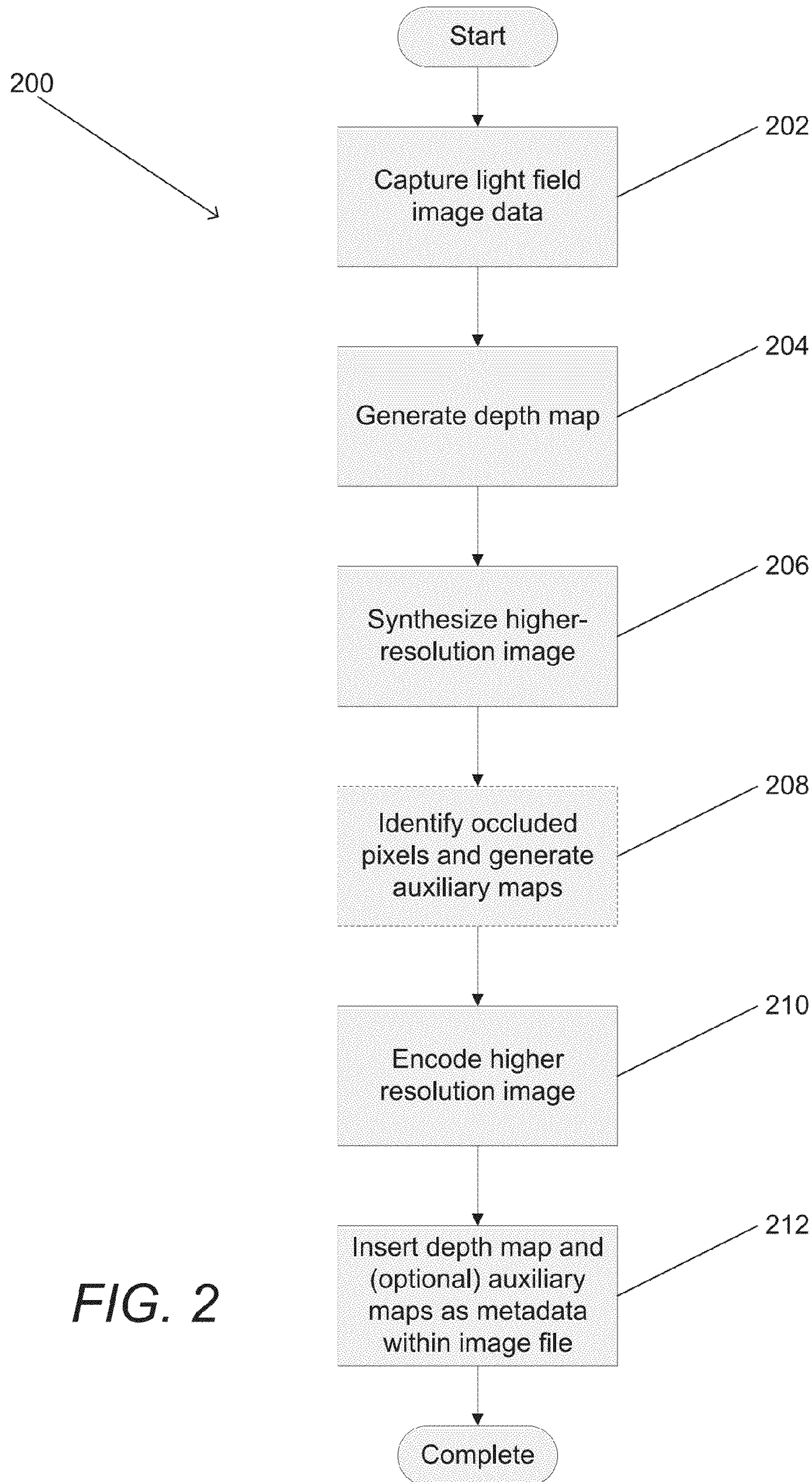


FIG. 2



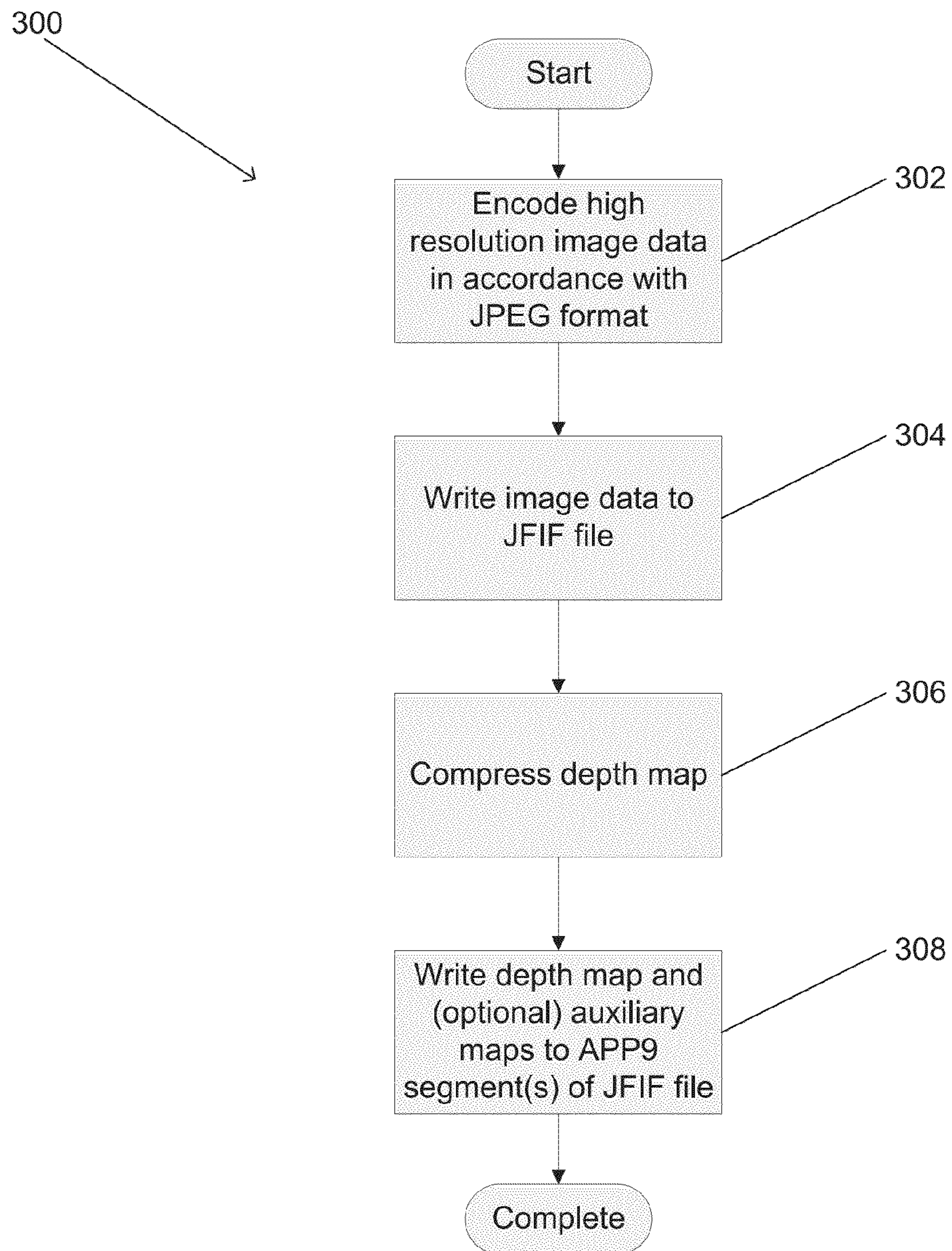


FIG. 3



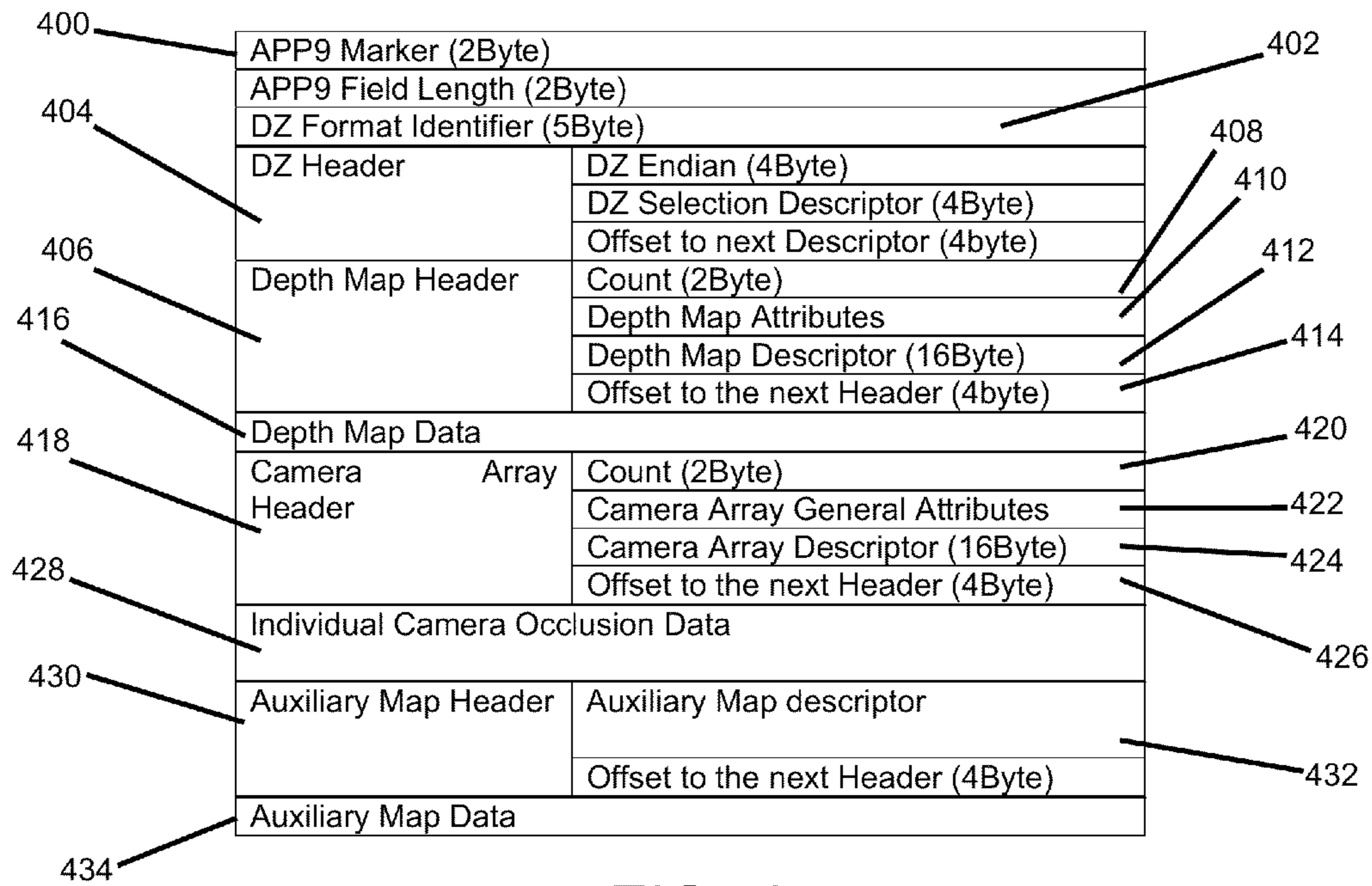


FIG. 4

Name	Byte number	Comments
Reserved for future extensions	Byte 3	
Number of Auxiliary Maps	Byte 2	Describes total number of Auxiliary maps present in the file
Depth Map Camera Array and Auxiliary Maps compression	Byte 1	See detailed description in Figure 6
Depth Map, Camera Array and Auxiliary Maps Selection	Byte 0	See detailed description in Figure 7

FIG. 5



Data Type	Bit number	Selection values
Reserved for Future extensions	Bit 7	
Confidence Map	Bit 7	0: Map is not included 1: Map is Present
Silhouette Edge Map	Bit 5	0: Map is not included 1: Map is Present
Regular Edge Map	Bit 4	0: Map is not included 1: Map is Present
Missing Pixel Map	Bit 3	0: Map is not included 1: Map is Present
Virtual View Point	Bit 2	0: No Virtual View Point 1: Virtual View Point is Present
Camera Array and Per camera Occlusion Data	Bit 1	0: Data is not included 1: Data are Present
Depth Map	Bit 0	0: Data is not included 1: Data is Present

**FIG. 6**

Reserved for Future extensions	Bit 7	0: Not Compressed 1: Compressed
Confidence Map	Bit 7	0: Not Compressed 1: Compressed
Silhouette Edge Map	Bit 5	0: Not Compressed 1: Compressed
Regular Edge Map	Bit 4	0: Not Compressed 1: Compressed
Missing Pixel Map	Bit 3	0: Not Compressed 1: Compressed
Virtual View Point	Bit 2	0: Not Present 1: Present
Camera Array and Per camera Occlusion Data	Bit 1	0: Not Compressed 1: Compressed
Depth Map	Bit 0	0: Regular JPEG compression 1: Lossless JPEG LS compression

**FIG. 7**



Attribute name	Attribute Tag ID (4Byte)	Attribute Description
Reserved for future extensions	2-127	
In Focus Plane	1	Define central in focus Depth Plane
F#	0	Defines Synthetic Aperture

**FIG. 8**

Name	Byte Number	Description	Comments
Reserved for future extensions	9-15		
Version	7-8	The most significant byte is used for major revisions, the least significant byte for minor revisions. Version 1.00 is the current revision.	Initial version must support Regular JPEG 8-bit grayscale compression
Identifier	0-6	Zero terminated string "PIDZDH" uniquely identifies this descriptor	

**FIG. 9**

Name	Byte Numbers	Description	Comments
Compressed Depth Map Data	16 to 16 + Length	Compressed Depth Map Data for Current Segment	
Reserved for future extensions	13-15		
Offset to the next Marker	9-12	Number of bites from current Marker to the next Marker excluding the APP9 marker itself	Next Marker could be either Depth Map Data Segment Marker, Camera Array Marker or Auxiliary Map Marker
Length	7-8	Total APP9 field byte count, including the byte count value (2 bytes), but excluding the APP9 marker itself.	A JPEG marker is limited to 65533 bytes. To represent the whole map multiple depth map markers with the same ID will be following each other
Identifier	0-6	Zero terminated string "PIDZDD" uniquely identifies this descriptor	

*FIG. 10*



Attribute name	Attribute Tag ID (4Byte)	Bytes	Attribute Description	Comments
Horizontal dimension	0	4	Number of cameras in horizontal direction N	We assume two dimensional Camera Array
Vertical dimension	1	4	Number of cameras in horizontal direction M	
Reference camera position	2	4	Camera number (row major)	
Virtual View Position	3	8	Two floating point numbers Px and Py defining Horizontal and Vertical position of Virtual View point	Constrains:  0 <= Px <= N  0 <= Py <= M
Number of cameras with occlusion data	4	4	Number of cameras in camera array with occlusion data	

**FIG. 11**

Name	Byte Number	Description	Comments
Reserved for future extensions	9-15		
Version	7-8	The most significant byte is used for major revisions, the least significant byte for minor revisions. Version 1.00 is the current revision.	Initial version must support Regular JPEG 8-bit grayscale compression
Identifier	0-6	Zero terminated string "PIDZAH" uniquely identifies this descriptor	

**FIG. 12**

Name	Byte Numbers	Description	Comments
Reserved for future extensions	14-15		
Offset to the next Marker	12-13	Number of bites from current Marker to the next Marker excluding the APP9 marker itself	Next Marker could be either Depth Map Data Segment Marker, Camera Array Marker or Auxiliary Map Marker
Length	10-11	Total APP9 field byte count, including the byte count value (2 bytes), but excluding the APP9 marker itself.	A JPEG marker is limited to 65533 bytes. To represent the whole map multiple depth map markers with the same ID will be following each other
Number of Occluded pixels	8-9	Total Number of Occluded Pixels in this Camera	Currently Camera Array Data is not compressed
Camera Number	7	Camera Number (row major)	
Identifier	0-6	Zero terminated string "PIDZCD" uniquely identifies this descriptor	

**FIG. 13**



Name	Byte Numbers	Description	Comments
Individual Camera Data for Current Segment	16 to 16 + Length	Occlusion Data	Occlusion Data in current revision is not compressed
Reserved for future extensions	12-15		
Offset to the next Marker	10-11	Number of bites from current Marker to the next Marker excluding the APP9 marker itself	Next Marker could be either Depth Map Data Segment Marker, Camera Array Marker or Auxiliary Map Marker
Length	8-9	Total APP9 field byte count, including the byte count value (2 bytes), but excluding the APP9 marker itself.	A JPEG marker is limited to 65533 bytes. To represent the whole map multiple depth map markers with the same ID will be following each other
Number of Pixels	7- 8	Number of occluded pixels in current segment	
Identifier	0-6	Zero terminated string "PIDZCD" uniquely identifies this descriptor	

**FIG. 14**

Name	Number of Bytes	Attribute Description	Comments
Depth	1	Depth value	
RGB Color	3	Pixel color	
Pixel coordinates	8	Two integer numbers defining x an y Pixel coordinates	

**FIG. 15**

Name	Byte Number	Description	Comments
Reserved for future extensions	11-15		
Number of bits per Map	10	Number of bits per pixel for current Auxiliary Map	
Auxiliary Map Type	9	Type of Auxiliary maps	The following types of Auxiliary Maps have been currently defined: 0 = Missing Pixel 1 = Regular Edge 2 = Silhouette Edge 3 = Confidence
Version	7-8	The most significant byte is used for major revisions, the least significant byte for minor revisions. Version 1.00 is the current revision.	Initial version must support Regular JPEG 8-bit grayscale compression
Identifier	0-6	Zero terminated string "PIDZAM" uniquely identifies this descriptor	

FIG. 16



Name	Byte Numbers	Description	Comments
Auxiliary Map Data	16 to 16 + Length	Auxiliary data	Not compressed in current revision
Reserved for future extensions	15		
Offset to the next Marker	11-14	Number of bites from current Marker to the next Marker excluding the APP9 marker itself	Next Marker could be either Depth Map Data Segment Marker, Camera Array Marker or Auxiliary Map Marker
Length	9-10	Total APP9 field byte count, including the byte count value (2 bytes), but excluding the APP9 marker itself.	A JPEG marker is limited to 65533 bytes. To represent the whole map multiple depth map markers with the same ID will be following each other
Number of pixels	7-8	Number of pixels in current segment	
Identifier	0-6	Zero terminated string "PIDZAD" uniquely identifies this descriptor	

*FIG. 17*

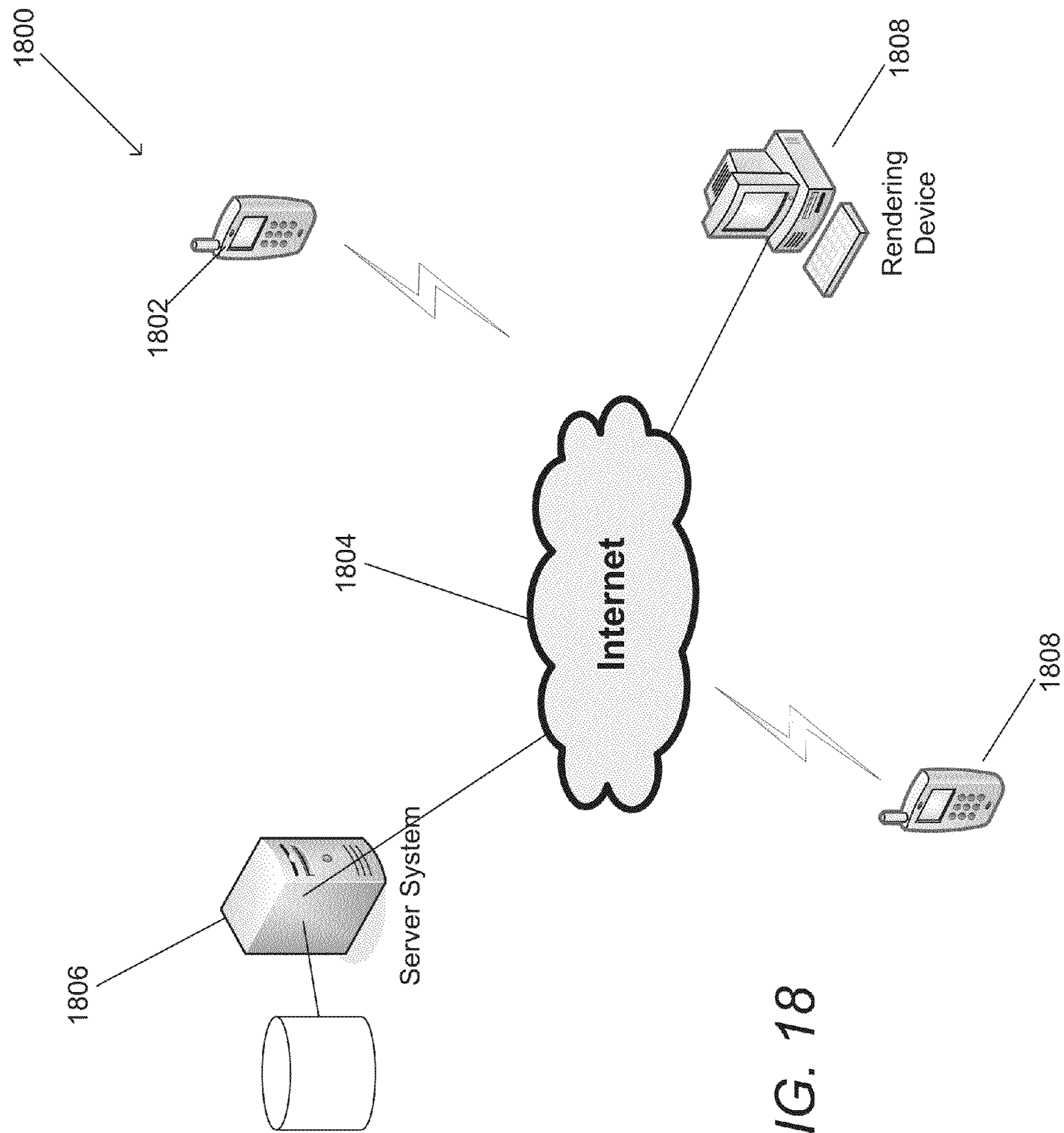


FIG. 18



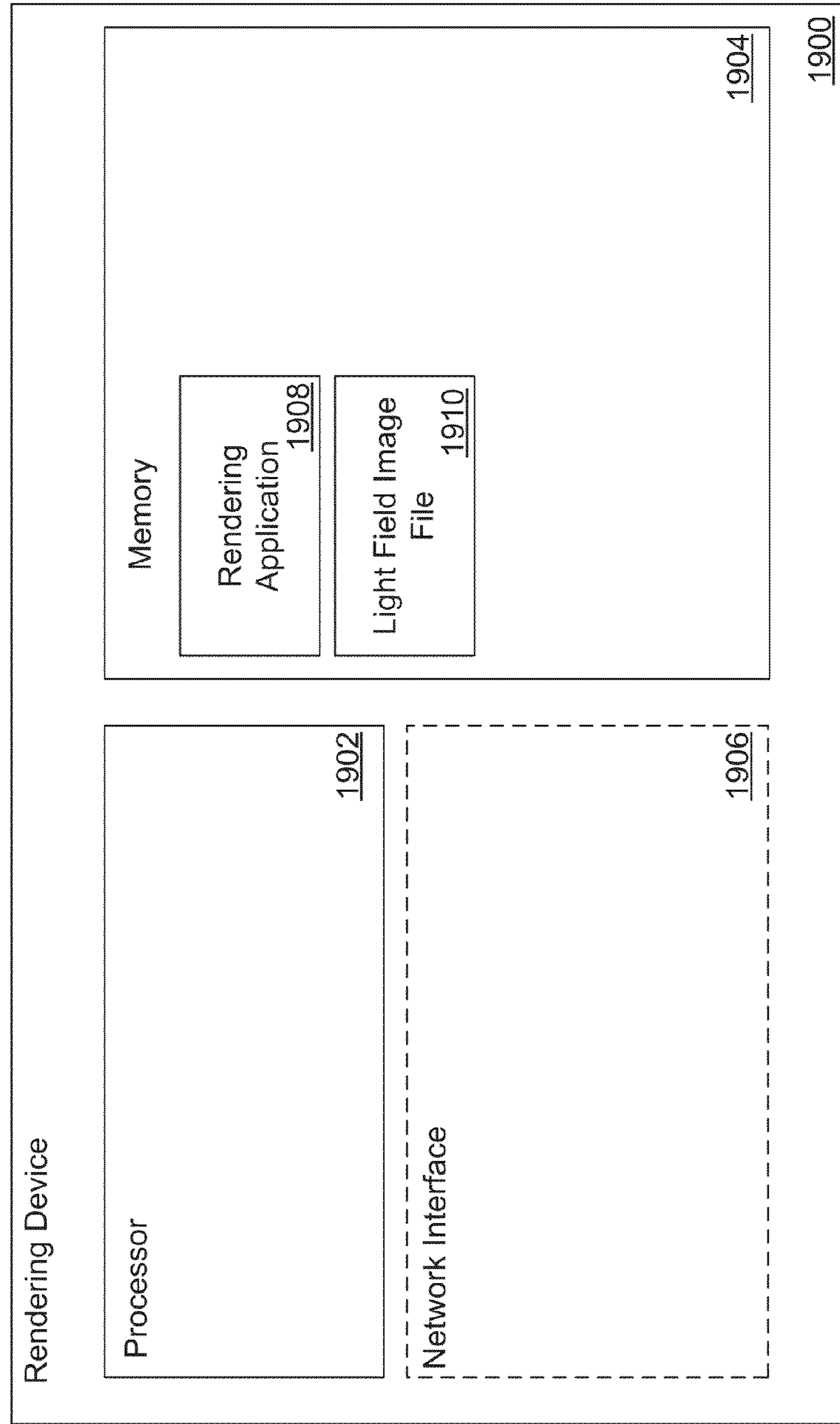


FIG. 19

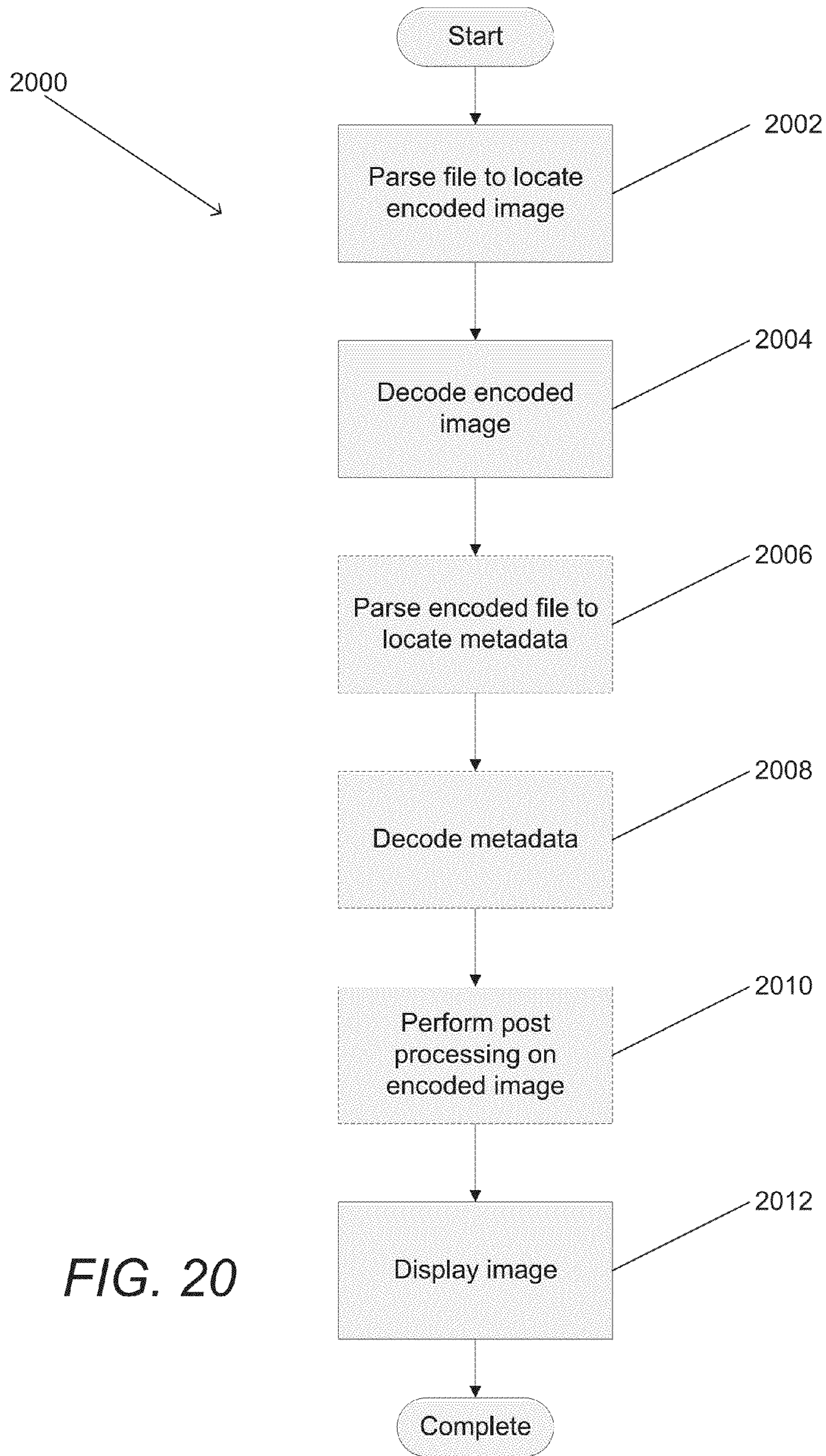


FIG. 20



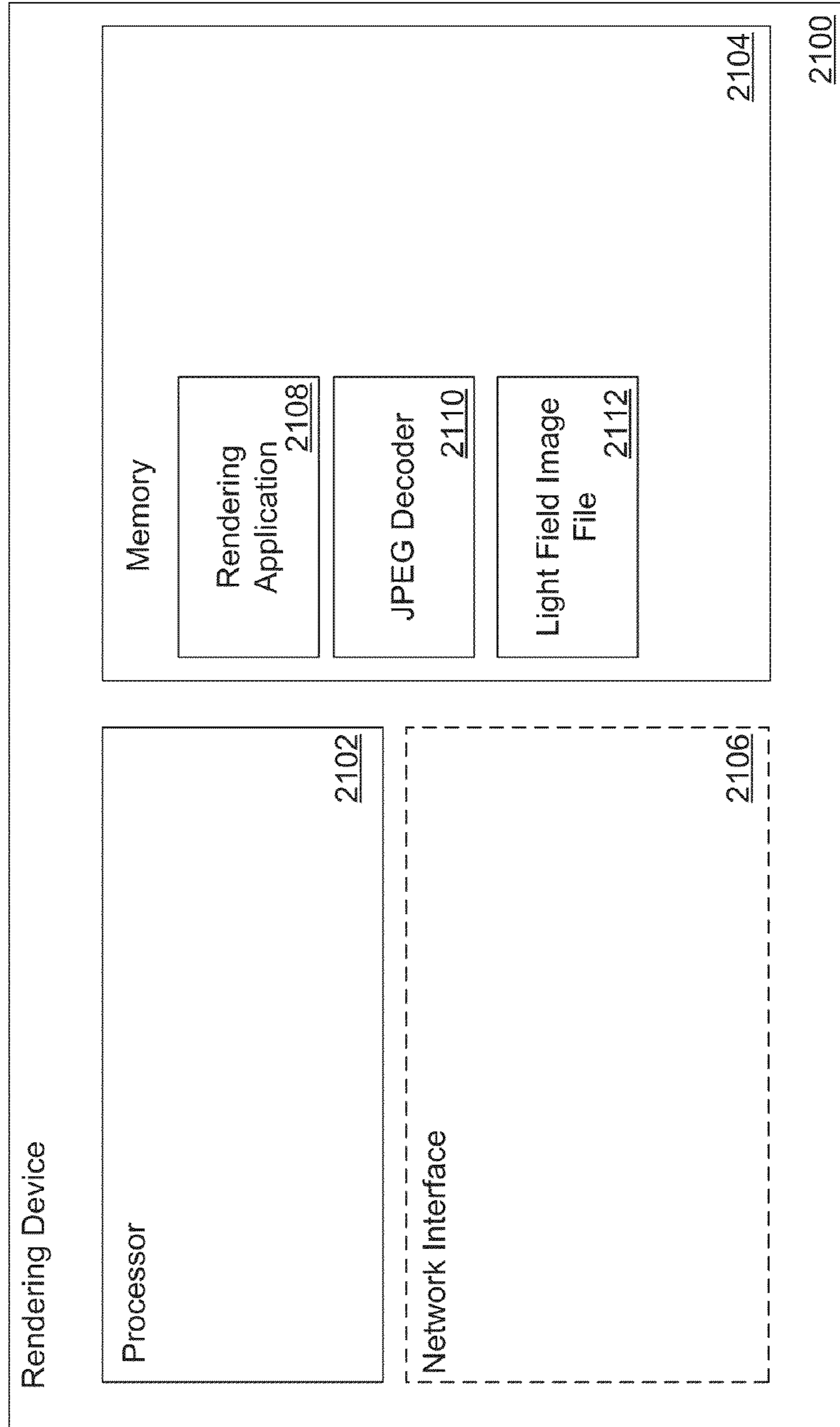


FIG. 21

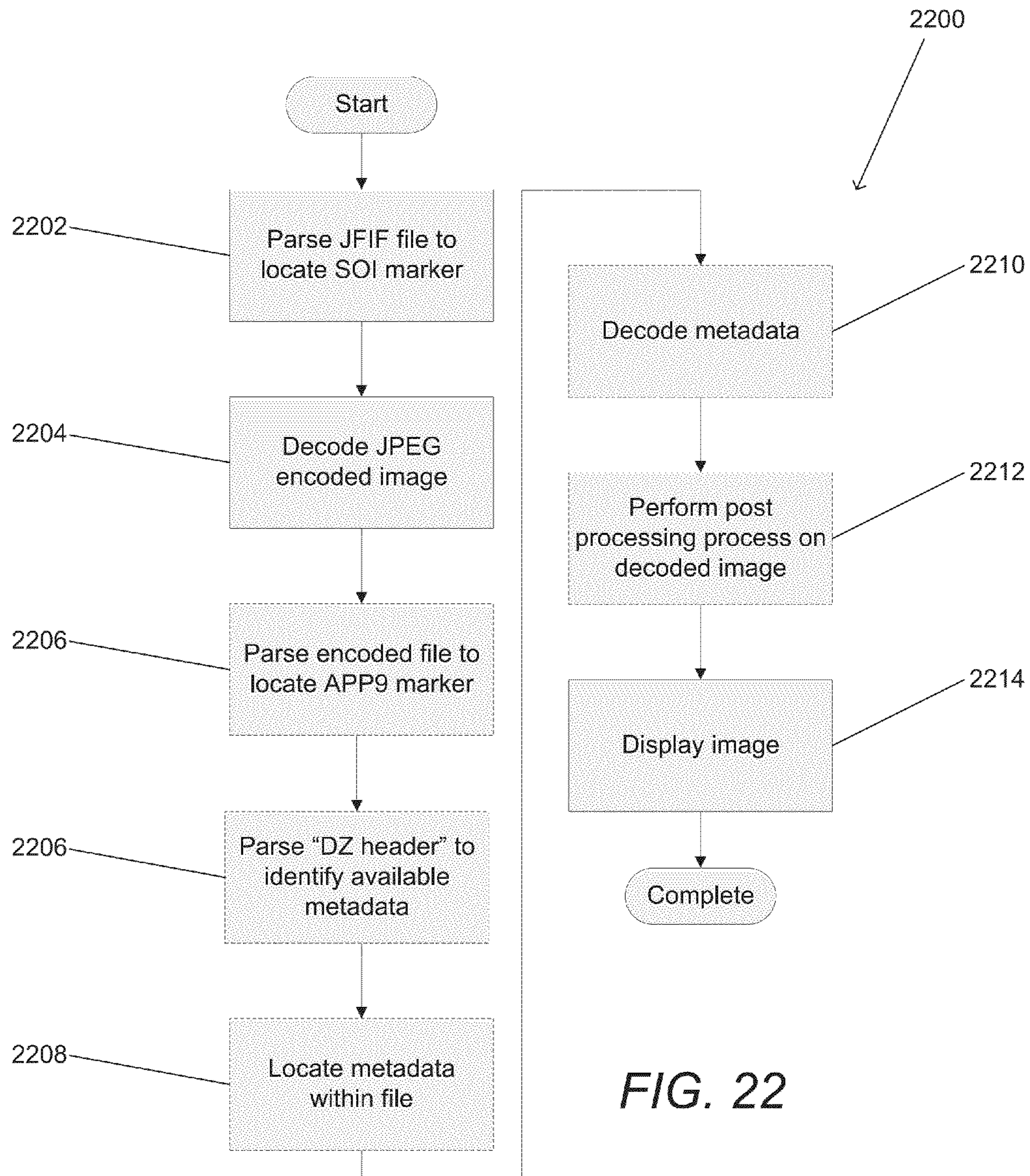


FIG. 22



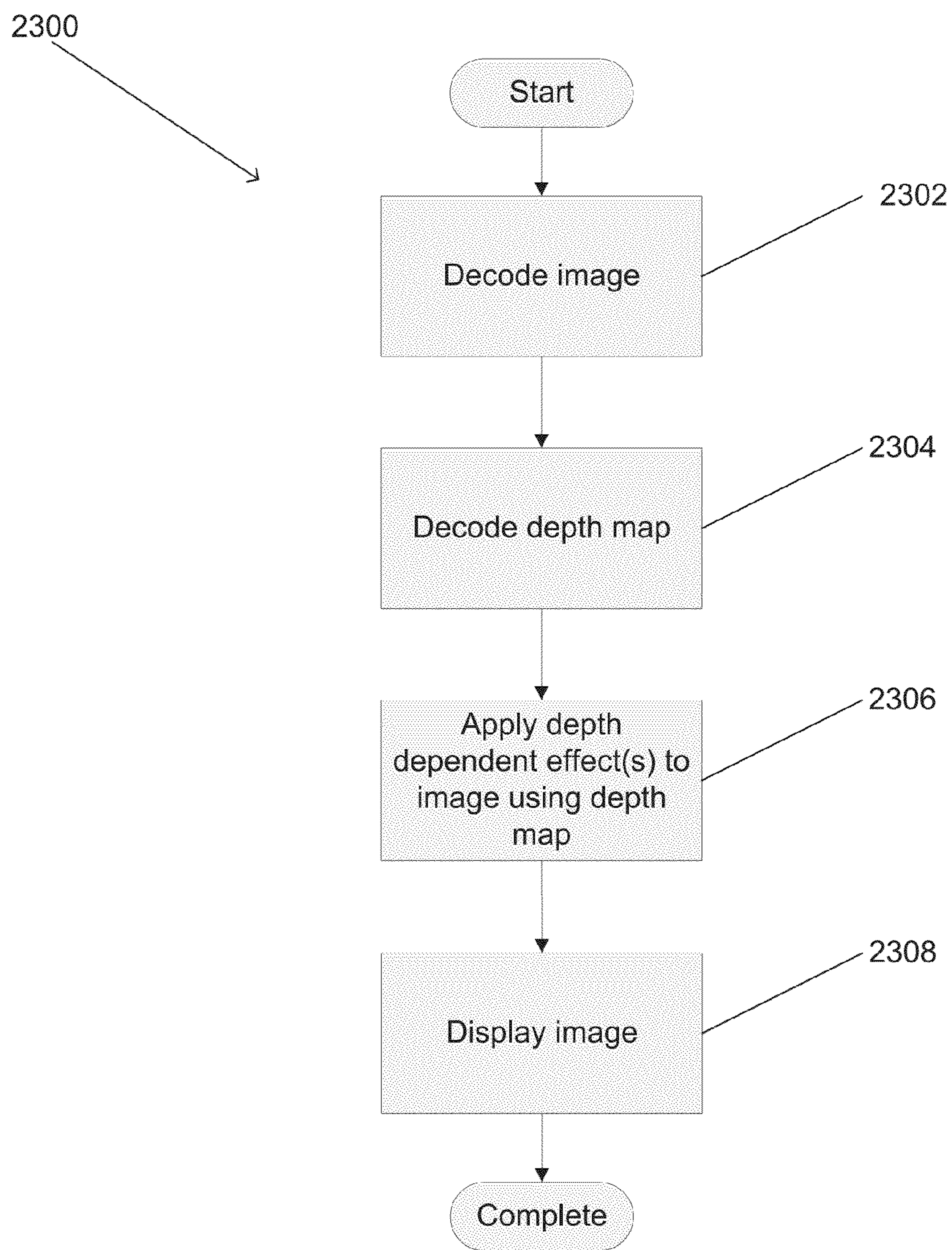


FIG. 23

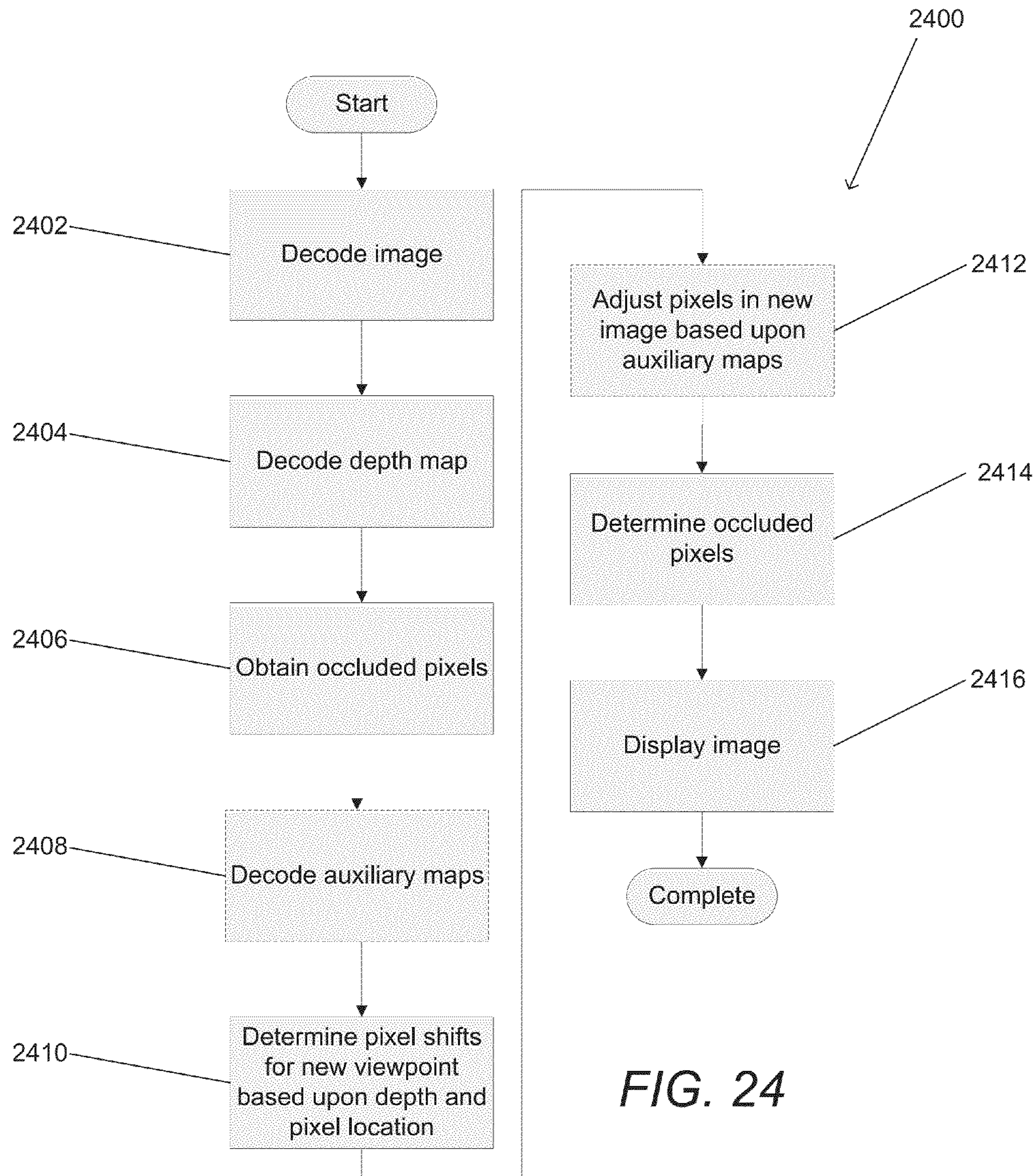


FIG. 24



## SYSTEMS AND METHODS FOR ENCODING STRUCTURED LIGHT FIELD IMAGE FILES

### CROSS-REFERENCE TO RELATED APPLICATION

The present invention is a continuation of U.S. patent application Ser. No. 13/631,731, filed Sep. 28, 2012, which claims priority to U.S. Provisional Application No. 61/540,188 entitled "JPEG-DX: A Backwards-compatible, Dynamic Focus Extension to JPEG", to Venkataraman et al. and filed Sep. 28, 2011, the disclosures of which are incorporated herein by reference in their entirety.

### FIELD OF THE INVENTION

The present invention relates to encoding of image files and more specifically to the encoding of light field image files.

### BACKGROUND

The ISO/IEC 10918-1 standard, more commonly referred to as the JPEG standard after the Joint Photographic Experts Group that developed the standard, establishes a standard process for digital compression and coding of still images. The JPEG standard specifies a codec for compressing an image into a bitstream and for decompressing the bitstream back into an image.

A variety of container file formats including the JPEG File Interchange Format (JFIF) specified in ISO/IEC 10918-5 and the Exchangeable Image File Format (Exif) and can be used to store a JPEG bitstream. JFIF can be considered a minimal file format that enables JPEG bitstreams to be exchanged between a wide variety of platforms and applications. The color space used in JFIF files is YCbCr as defined by CCIR Recommendation 601, involving 256 levels. The Y, Cb, and Cr components of the image file are converted from R, G, and B, but are normalized so as to occupy the full 256 levels of an 8-bit binary encoding. YCbCr is one of the compression formats used by JPEG. Another popular option is to perform compression directly on the R, G and B color planes. Direct RGB color plane compression is also popular when lossless compression is being applied.

A JPEG bitstream stores 16-bit word values in big-endian format. JPEG data in general is stored as a stream of blocks, and each block is identified by a marker value. The first two bytes of every JPEG bitstream are the Start Of Image (SOI) marker values FFh D8h. In a JFIF-compliant file there is a JFIF APP0 (Application) marker, immediately following the SOI, which consists of the marker code values FFh E0h and the characters JFIF in the marker data, as described in the next section. In addition to the JFIF marker segment, there may be one or more optional JFIF extension marker segments, followed by the actual image data.

Overall the JFIF format supports sixteen "Application markers" to store metadata. Using application markers makes it possible for a decoder to parse a JFIF file and decode only required segments of image data. Application markers are limited to 64K bytes each but it is possible to use the same maker ID multiple times and refer to different memory segments.

An APP0 marker after the SOI marker is used to identify a JFIF file. Additional APP0 marker segments can optionally be used to specify JFIF extensions. When a decoder does not support decoding a specific JFIF application marker, the decoder can skip the segment and continue decoding.

One of the most popular file formats used by digital cameras is Exif. When Exif is employed with JPEG bitstreams, an APP1 Application marker is used to store the Exif data. The Exif tag structure is borrowed from the Tagged Image File Format (TIFF) maintained by Adobe Systems Incorporated of San Jose, Calif.

### SUMMARY OF THE INVENTION

Systems and methods in accordance with embodiments of the invention are configured to store images synthesized from light field image data and metadata describing the images in electronic files. One embodiment of the invention includes a processor and memory containing an encoding application and light field image data, where the light field image data comprises a plurality of low resolution images of a scene captured from different viewpoints. In addition, the encoding application configures the processor to: synthesize a higher resolution image of the scene from a reference viewpoint using the low resolution images, where synthesizing the higher resolution image involves creating a depth map that specifies depths from the reference viewpoint for pixels in the higher resolution image; encode the higher resolution image; and create a light field image file including the encoded image and metadata describing the encoded image, where the metadata includes the depth map.

In a further embodiment, the encoding application configures the processor to encode the depth map and the depth map included in the metadata describing the encoded image is the encoded depth map.

In another embodiment, synthesizing the higher resolution image involves identifying pixels in the plurality of low resolution images of the scene that are occluded in the reference viewpoint, and the metadata describing the encoded image in the light field image file includes descriptions of the occluded pixels.

In a still further embodiment, the descriptions of the occluded pixels include colors, locations, and depths of the occluded pixels.

In still another embodiment, synthesizing the higher resolution image involves creating a confidence map for the depth map, where the confidence map indicates the reliability of the depth value for a pixel in the depth map, and the metadata describing the encoded image in the light field image file includes the confidence map.

In a yet further embodiment, the encoding application configures the processor to encode the confidence map.

In yet another embodiment, the encoding application configures the processor to generate an edge map that indicates pixels in the synthesized image that lie on a discontinuity, and the metadata describing the encoded image in the light field image file includes the edge map.

In a further embodiment again, the edge map identifies whether a pixel lies on an intensity discontinuity.

In another embodiment again, the edge map identifies whether a pixel lies on an intensity and depth discontinuity.

In a further additional embodiment, the encoding application configures the processor to encode the edge map.

In another additional embodiment, the encoding application configures the processor to generate a missing pixel map that indicates pixels in the synthesized image that do not correspond to a pixel from the plurality of low resolution images of the scene and that are generated by interpolating pixel values from adjacent pixels in the synthesized image, and the metadata describing the encoded image in the light field image file includes the missing pixels map.



In a still yet further embodiment, the encoding application configures the processor to encode the missing pixels map.

In still yet another embodiment, the metadata also includes a focal plane.

In a still further embodiment again, the light field image file conforms to the JFIF standard.

In still another embodiment again, the high resolution image is encoded in accordance with the JPEG standard.

In a still further additional embodiment, the metadata is located within an Application marker segment within the light field image file.

In still another additional embodiment, the Application marker segment is identified using the APPS marker.

In a yet further embodiment again, the encoding application configures the processor to encode the depth map in accordance with the JPEG standard using lossless compression and the encoded depth map is stored within the Application marker segment containing the metadata.

In yet another embodiment again, synthesizing the higher resolution images involves identifying pixels from the plurality of low resolution images of the scene that are occluded in the reference viewpoint, and descriptions of the occluded pixels are stored within the Application marker segment containing the metadata.

In a yet further additional embodiment, the descriptions of the occluded pixels include colors, locations, and depths of the occluded pixels.

In yet another additional embodiment, synthesizing the higher resolution image involves creating a confidence map for the depth map, where the confidence map indicates the reliability of the depth value for a pixel in the depth map, and the confidence map is stored within the Application marker segment containing the metadata.

In a further additional embodiment again, the encoding application configures the processor to encode the confidence map in accordance with the JPEG standard using lossless compression.

In another additional embodiment again, the encoding application configures the processor to generate an edge map that indicates pixels in the synthesized image that lie on a discontinuity, and the edge map is stored within the Application marker segment containing the metadata.

In a still yet further embodiment again, the edge map identifies whether a pixel lies on an intensity discontinuity.

In still yet another embodiment again, the edge map identifies whether a pixel lies on an intensity and depth discontinuity.

In a still yet further additional embodiment, the encoding application configures the processor to encode the edge map in accordance with the JPEG standard using lossless compression.

In still yet another additional embodiment, the encoding application configures the processor to generate a missing pixel map that indicates pixels in the synthesized image that do not correspond to a pixel from the plurality of low resolution images of the scene and that are generated by interpolating pixel values from adjacent pixels in the synthesized image, and the missing pixel map is stored within the Application marker segment containing the metadata.

In a yet further additional embodiment again, the encoding application configures the processor to encode the missing pixels map in accordance with the JPEG standard using lossless compression.

An embodiment of the method of the invention includes synthesizing a higher resolution image of a scene from a reference viewpoint and a depth map that describes depths of pixels in the synthesized image using an encoding device and

light field image data, where the light field image data comprises a plurality of low resolution images of a scene captured from different viewpoints and synthesizing the higher resolution image includes creating a depth map that specifies depths from the reference viewpoint for pixels in the higher resolution image, encoding the higher resolution image using the encoding device, and creating a light field image file including the encoded image and metadata describing the encoded image using the encoding device, where the metadata includes the depth map.

Another embodiment of the invention includes a machine readable medium containing processor instructions, where execution of the instructions by a processor causes the processor to perform a process involving: synthesizing a higher resolution image of a scene from a reference viewpoint using light field image data, where the light field image data comprises a plurality of low resolution images of a scene captured from different viewpoints and synthesizing the higher resolution image includes creating a depth map that specifies depths from the reference viewpoint for pixels in the higher resolution image; encoding the higher resolution image; and creating a light field image file including the encoded image and metadata describing the encoded image, where the metadata includes the depth map.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 conceptually illustrates the architecture of an array camera configured to generate light field image files in accordance with embodiments of the invention.

FIG. 2 is a flow chart of a process for creating a light field image file including an image synthesized from light field image data and a depth map for the synthesized image generated using the light field image data in accordance with an embodiment of the invention.

FIG. 3 is a process for creating a light field image file that conforms to the JFIF standard and that includes an image encoded in accordance with the JPEG standard in accordance with an embodiment of the invention.

FIG. 4 illustrates an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 5 illustrates a "DZ Selection Descriptor" contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 6 illustrates a "Depth Map, Camera Array and Auxiliary Maps Selection Descriptor" contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 7 illustrates a "Depth Map, Camera Array and Auxiliary Maps Compression Descriptor" contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 8 illustrates a "Depth Map Attributes" field within a "Depth Map Header" contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 9 illustrates a "Depth Map Descriptor" field within a "Depth Map Header" contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.



FIG. 10 illustrates a “Depth Map Data Descriptor” contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 11 illustrates a “Camera Array Attributes” field within a “Camera Array Header” contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 12 illustrates a “Camera Array Descriptor” field within a “Camera Array Header” contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 13 illustrates an “Individual Camera Descriptor” contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 14 illustrates “Individual Camera Data” within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 15 illustrates an “Individual Pixel Data Structure” within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 16 illustrates an “Auxiliary Map Descriptor” within an “Auxiliary Map Header” contained within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 17 illustrates an “Auxiliary Map Data Descriptor” within an APP9 Application marker segment of a light field image file that conforms to the JFIF standard in accordance with an embodiment of the invention.

FIG. 18 illustrates a network including at least one encoding device configured to capture light field image data and encode light field image files and to share the light field image file with rendering devices via a network in accordance with an embodiment of the invention.

FIG. 19 conceptually illustrates a rendering device configured by a rendering application to render an image using a light field image file.

FIG. 20 is a flow chart illustrating a process for rendering an image using a light field image file in accordance with an embodiment of the invention.

FIG. 21 conceptually illustrates a rendering device configured by a rendering application to render an image using a light field image file containing an image and/or a map encoded in accordance with the JPEG standard.

FIG. 22 is a flow chart illustrating a process for rendering an image using a light field image file that conforms to the JFIF standard and includes an image encoded in accordance with the JPEG standard and metadata describing the encoded image.

FIG. 23 is a flow chart illustrating a process applying depth dependent effects to an encoded image contained within the light field image file based upon a depth map contained within the light field image file in accordance with an embodiment of the invention.

FIG. 24 is a flow chart illustrating a process for rendering an image from a different viewpoint to a reference viewpoint of an image contained within a light field image file in accordance with an embodiment of the invention.

#### DETAILED DESCRIPTION

Turning now to the drawings, systems and methods for storing images synthesized from light field image data and

metadata describing the images in electronic files and for rendering images using the stored images and metadata in accordance with embodiments of the invention are illustrated. A file containing an image synthesized from light field image data and metadata derived from the light field image data can be referred to as a light field image file. As is discussed further below, the encoded image in a light field image file is typically synthesized using a super resolution process from a number of lower resolution images. The light field image file can also include metadata describing the synthesized image derived from the light field image data that enables post processing of the synthesized image. In many embodiments, a light field image file is created by encoding an image synthesized from light field image data and combining the encoded image with a depth map derived from the light field image data. In several embodiments, the encoded image is synthesized from a reference viewpoint and the metadata includes information concerning pixels in the light field image that are occluded from the reference viewpoint. In a number of embodiments, the metadata can also include additional information including (but not limited to) auxiliary maps such as confidence maps, edge maps, and missing pixel maps that can be utilized during post processing of the encoded image to improve the quality of an image rendered using the light field image data file.

In many embodiments, the light field image file is compatible with the JPEG File Interchange Format (JFIF). The synthesized image is encoded as a JPEG bitstream and stored within the file. The accompanying depth map, occluded pixels and/or any appropriate additional information including (but not limited to) auxiliary maps are then stored within the JFIF file as metadata using an Application marker to identify the metadata. A legacy rendering device can simply display the synthesized image by decoding the JPEG bitstream. Rendering devices in accordance with embodiments of the invention can perform additional post-processing on the decoded JPEG bitstream using the depth map and/or any available auxiliary maps. In many embodiments, the maps included in the metadata can also be compressed using lossless JPEG encoding and decoded using a JPEG decoder. Although much of the discussion that follows references the JFIF and JPEG standards, these standards are simply discussed as examples and it should be appreciated that similar techniques can be utilized to embed metadata derived from light field image data used to synthesize the encoded image within a variety of standard file formats, where the synthesized image and/or maps are encoded using any of a variety of standards based image encoding processes.

By transmitting a light field image file including an encoded image, and metadata describing the encoded image, a rendering device (i.e. a device configured to generate an image rendered using the information within the light field image file) can render new images using the information within the file without the need to perform super resolution processing on the original light field image data. In this way, the amount of data transmitted to the rendering device and the computational complexity of rendering an image is reduced. In several embodiments, rendering devices are configured to perform processes including (but not limited to) refocusing the encoded image based upon a focal plane specified by the user, synthesizing an image from a different viewpoint, and generating a stereo pair of images. The capturing of light field image data and the encoding and decoding of light field image files in accordance with embodiments of the invention are discussed further below.

#### 65 Capturing Light Field Image Data

A light field, which is often defined as a 4D function characterizing the light from all direction at all points in a



scene, can be interpreted as a two-dimensional (2D) collection of 2D images of a scene. Array cameras, such as those described in U.S. patent application Ser. No. 12/935,504 entitled "Capturing and Processing of Images using Monolithic Camera Array with Heterogeneous Imagers" to Venkataraman et al., can be utilized to capture light field images. In a number of embodiments, super resolution processes such as those described in U.S. patent application Ser. No. 12/967,807 entitled "Systems and Methods for Synthesizing High Resolution Images Using Super-Resolution Processes" to Lelescu et al., are utilized to synthesize a higher resolution 2D image or a stereo pair of higher resolution 2D images from the lower resolution images in the light field captured by an array camera. The terms high or higher resolution and low or lower resolution are used here in a relative sense and not to indicate the specific resolutions of the images captured by the array camera. The disclosures of U.S. patent application Ser. No. 12/935,504 and U.S. patent application Ser. No. 12/967,807 are hereby incorporated by reference in their entirety.

Each two-dimensional (2D) image in a captured light field is from the viewpoint of one of the cameras in the array camera. A high resolution image synthesized using super resolution processing is synthesized from a specific viewpoint that can be referred to as a reference viewpoint. The reference viewpoint can be from the viewpoint of one of the cameras in a camera array. Alternatively, the reference viewpoint can be an arbitrary virtual viewpoint.

Due to the different viewpoint of each of the cameras, parallax results in variations in the position of foreground objects within the images of the scene. Processes for performing parallax detection are discussed in U.S. Provisional Patent Application Ser. No. 61/691,666 entitled "Systems and Methods for Parallax Detection and Correction in Images Captured Using Array Cameras" to Venkataraman et al., the disclosure of which is incorporated by reference herein in its entirety. As is disclosed in U.S. Provisional Patent Application Ser. No. 61/691,666, a depth map from a reference viewpoint can be generated by determining the disparity between the pixels in the images within a light field due to parallax. A depth map indicates the distance of the surfaces of scene objects from a reference viewpoint. In a number of embodiments, the computational complexity of generating depth maps is reduced by generating an initial low resolution depth map and then increasing the resolution of the depth map in regions where additional depth information is desirable such as (but not limited to) regions involving depth transitions and/or regions containing pixels that are occluded in one or more images within the light field.

During super resolution processing, a depth map can be utilized in a variety of ways. U.S. patent application Ser. No. 12/967,807 describes how a depth map can be utilized during super resolution processing to dynamically refocus a synthesized image to blur the synthesized image to make portions of the scene that do not lie on the focal plane to appear out of focus. U.S. patent application Ser. No. 12/967,807 also describes how a depth map can be utilized during super resolution processing to generate a stereo pair of higher resolution images for use in 3D applications. A depth map can also be utilized to synthesize a high resolution image from one or more virtual viewpoints. In this way, a rendering device can simulate motion parallax and a dolly zoom (i.e. virtual viewpoints in front or behind the reference viewpoint). In addition to utilizing a depth map during super-resolution processing, a depth map can be utilized in a variety of post processing processes to achieve effects including (but not limited to) dynamic refocusing, generation of stereo pairs, and generation of virtual viewpoints without performing super-resolu-

tion processing. Light field image data captured by array cameras, storage of the light field image data in a light field image file, and the rendering of images using the light field image file in accordance with embodiments of the invention are discussed further below.

#### Array Camera Architecture

Array cameras in accordance with embodiments of the invention are configured so that the array camera software can control the capture of light field image data and can capture the light field image data into a file that can be used to render one or more images on any of a variety of appropriately configured rendering devices. An array camera including an imager array in accordance with an embodiment of the invention is illustrated in FIG. 1. The array camera **100** includes a sensor **102** having an array of focal planes **104** and which is configured to communicate with a processor **108**. The processor is also configured to communicate with one or more different types of memory **110** that can be utilized to store image data and/or contain machine readable instructions utilized to configure the processor to perform processes including (but not limited to) the various processes described below. The array camera **100** also includes a display **112** that can be utilized by the processor **108** to present a user interface to a user and to display an image rendered using the light field image data. Although the processor is illustrated as a single processor, array cameras in accordance with embodiments of the invention can utilize a single processor or multiple processors including (but not limited to) a graphics processing unit (GPU).

In the illustrated embodiment, the processor receives image data generated by the sensor and reconstructs the light field captured by the sensor from the image data. The processor can manipulate the light field in any of a variety of different ways including (but not limited to) determining the depth and visibility of the pixels in the light field and synthesizing higher resolution 2D images from the image data of the light field. Sensors including multiple focal planes are discussed in U.S. patent application Ser. No. 13/106,797 entitled "Architectures for System on Chip Array Cameras", to Pain et al., the disclosure of which is incorporated herein by reference in its entirety.

In the illustrated embodiment, the focal planes are configured in a 5x5 array. Each focal plane **104** on the sensor is capable of capturing an image of the scene. The sensor elements utilized in the focal planes can be individual light sensing elements such as, but not limited to, traditional CIS (CMOS Image Sensor) pixels, CCD (charge-coupled device) pixels, high dynamic range sensor elements, multispectral sensor elements and/or any other structure configured to generate an electrical signal indicative of light incident on the structure. In many embodiments, the sensor elements of each focal plane have similar physical properties and receive light via the same optical channel and color filter (where present). In other embodiments, the sensor elements have different characteristics and, in many instances, the characteristics of the sensor elements are related to the color filter applied to each sensor element.

In many embodiments, an array of images (i.e. a light field) is created using the image data captured by the focal planes in the sensor. As noted above, processors **108** in accordance with many embodiments of the invention are configured using appropriate software to take the image data within the light field and synthesize one or more high resolution images. In several embodiments, the high resolution image is synthesized from a reference viewpoint, typically that of a reference focal plane **104** within the sensor **102**. In many embodiments, the processor is able to synthesize an image from a virtual



viewpoint, which does not correspond to the viewpoints of any of the focal planes **104** in the sensor **102**. Unless all of the objects within a captured scene are a significant distance from the array camera, the images in the light field will include disparity due to the different fields of view of the focal planes used to capture the images. Processes for detecting and correcting for disparity when performing super-resolution processing in accordance with embodiments of the invention are discussed in U.S. Provisional Patent Application Ser. No. 61/691,666 (incorporated by reference above). The detected disparity can be utilized to generate a depth map. The high resolution image and depth map can be encoded and stored in memory **110** in a light field image file. The processor **108** can use the light field image file to render one or more high resolution images. The processor **108** can also coordinate the sharing of the light field image file with other devices (e.g. via a network connection), which can use the light field image file to render one or more high resolution images.

Although a specific array camera architecture is illustrated in FIG. 1, alternative architectures can also be utilized in accordance with embodiments of the invention. Systems and methods for encoding high resolution images and depth maps for storage in electronic files in accordance with embodiments of the invention are discussed below.

#### Capturing and Storing Light Field Image Data

Processes for capturing and storing light field image data in accordance with many embodiments of the invention involve capturing light field image data, generating a depth map from a reference viewpoint, and using the light field image data and the depth map to synthesize an image from the reference viewpoint. The synthesized image can then be compressed for storage. The depth map and additional data that can be utilized in the post processing can also be encoded as metadata that can be stored in the same container file with the encoded image.

A process for capturing and storing light field image data in accordance with an embodiment of the invention is illustrated in FIG. 2. The process **200** includes capturing (**202**) light field image data. In several embodiments, the light field image data is captured using an array camera similar to the array cameras described above. In other embodiments, any of a variety of image capture device(s) can be utilized to capture light field image data. The light field image data is used to generate (**204**) a depth map. A depth map can be generated using any of a variety of techniques including (but not limited to) using any of the processes disclosed in U.S. Provisional Patent Application Ser. No. 61/691,666 or U.S. patent application Ser. No. 13/623,091 entitled "Systems and Methods for Determining Depth from Multiple Views of a Scene that Include Aliasing Using Hypothesized Fusion", to Venkatarman et al. The disclosure of U.S. patent Ser. No. 13/623,091 is incorporated by reference herein in its entirety.

The light field image data and the depth map can be utilized to synthesize (**206**) an image from a specific viewpoint. In many embodiments, the light field image data includes a number of low resolution images that are used to synthesize a higher resolution image using a super resolution process. In a number of embodiments, a super resolution process such as (but not limited to) any of the super resolution processes disclosed in U.S. patent application Ser. No. 12/967,807 can be utilized to synthesize a higher resolution image from the reference viewpoint.

In order to be able to perform post processing to modify the synthesized image without the original light field image data, metadata can be generated (**208**) from the light field image data, the synthesized image, and/or the depth map. The metadata can be included in a light field image file and utilized

during post processing of the synthesized image to perform processing including (but not limited to) refocusing the encoded image based upon a focal plane specified by the user, and synthesizing one or more images from a different viewpoint. In a number of embodiments, the auxiliary data includes (but is not limited to) pixels in the light field image data occluded from the reference viewpoint used to synthesize the image from the light field image data, one or more auxiliary maps including (but not limited to) a confidence map, an edge map, and/or a missing pixel map. Auxiliary data that is formatted as maps or layers provide information corresponding to pixel locations within the synthesized image. A confidence map is produced during the generation of a depth map and reflects the reliability of the depth value for a particular pixel. This information may be used to apply different filters in areas of the image and improve image quality of the rendered image. An edge map defines which pixels are edge pixels, which enables application of filters that refine edges (e.g. post sharpening). A missing pixel map represents pixels computed by interpolation of neighboring pixels and enables selection of post-processing filters to improve image quality. As can be readily appreciated, the specific metadata generated depends upon the post processing supported by the image data file. In a number of embodiments, no auxiliary data is included in the image data file.

In order to generate an image data file, the synthesized image is encoded (**210**). The encoding typically involves compressing the synthesized image and can involve lossless or lossy compression of the synthesized image. In many embodiments, the depth map and any auxiliary data are written (**212**) to a file with the encoded image as metadata to generate a light field image data file. In a number of embodiments, the depth map and/or the auxiliary maps are encoded. In many embodiments, the encoding involves lossless compression.

Although specific processes for encoding light field image data for storage in a light field image file are discussed above, any of a variety of techniques can be utilized to process light field image data and store the results in an image file including but not limited to processes that encode low resolution images captured by an array camera and calibration information concerning the array camera that can be utilized in super resolution processing. Storage of light field image data in JFIF files in accordance with embodiments of the invention is discussed further below.

#### Image Data Formats

In several embodiments, the encoding of a synthesized image and the container file format utilized to create the light field image file are based upon standards including but not limited to the JPEG standard (ISO/IEC 10918-1) for encoding a still image as a bitstream and the JFIF standard (ISO/IEC 10918-5). By utilizing these standards, the synthesized image can be rendered by any rendering device configured to support rendering of JPEG images contained within JFIF files. In many embodiments, additional data concerning the synthesized image such as (but not limited to) a depth map and auxiliary data that can be utilized in the post processing of the synthesized image can be stored as metadata associated with an Application marker within the JFIF file. Conventional rendering devices can simply skip Application markers containing this metadata. Rendering device in accordance with many embodiments of the invention can decode the metadata and utilize the metadata in any of a variety of post processing processes.

A process for encoding an image synthesized using light field image data in accordance with the JPEG specification and for including the encoded image and metadata that can be



utilized in the post processing of the image in a JFIF file in accordance with an embodiment of the invention is illustrated in FIG. 3. The process 300 includes encoding (302) an image synthesized from light field image data in accordance with the JPEG standard. The image data is written (304) to a JFIF file. A depth map for the synthesized image is compressed (306) and the compressed depth map and any additional auxiliary data are written (308) as metadata to an Application marker segment of the JFIF file containing the encoded image. Where the auxiliary data includes maps, the maps can also be compressed by encoding the maps in accordance with the JPEG standard. At which point, the JFIF file contains an encoded image and metadata that can be utilized to perform post processing on the encoded image in ways that utilize the additional information captured in the light field image data utilized to synthesize the high resolution image (without the need to perform super resolution processing on the underlying light field image data).

Although specific processes are discussed above for storing light field image data in JFIF files, any of a variety of processes can be utilized to encode synthesized images and additional metadata derived from the light field image data used to synthesize the encoded images in a JFIF file as appropriate to the requirements of a specific application in accordance with embodiments of the invention. The encoding of synthesized images and metadata for insertion into JFIF files in accordance with embodiments of the invention are discussed further below. Although much of the discussion that follows relates to JFIF files, synthesized images and metadata can be encoded for inclusion in a light field image file using any of a variety of proprietary or standards based encoding techniques and/or utilizing any of a variety of proprietary or standards based file formats.

#### Encoding Images Synthesized from Light Field Image Data

An image synthesized from light field image data using super resolution processing can be encoded in accordance with the JPEG standard for inclusion in a light field image file in accordance with embodiments of the invention. The JPEG standard is a lossy compression standard. However, the information losses typically do not impact edges of objects. Therefore, the loss of information during the encoding of the image typically does not impact the accuracy of maps generated based upon the synthesized image (as opposed to the encoded synthesized image). The pixels within images contained within files that comply with the JFIF standard are typically encoded as YCbCr values. Many array cameras synthesize images, where each pixel is expressed in terms of a Red, Green and Blue intensity value. In several embodiments, the process of encoding the synthesized image involves mapping the pixels of the image from the RGB domain to the YCbCr domain prior to encoding. In other embodiments, mechanisms are used within the file to encode the image in the RGB domain. Typically, encoding in the YCbCr domain provides better compression ratios and encoding in the RGB domain provides higher decoded image quality.

#### Storing Additional Metadata Derived from Light Field Image Data

The JFIF standard does not specify a format for storing depth maps or auxiliary data generated by an array camera. The JFIF standard does, however, provide sixteen Application markers that can be utilized to store metadata concerning the encoded image contained within the file. In a number of embodiments, one or more of the Application markers of a JFIF file is utilized to store an encoded depth map and/or one or more auxiliary maps that can be utilized in the post processing of the encoded image contained within the file.

A JFIF Application marker segment that can be utilized to store a depth map, individual camera occlusion data and auxiliary map data in accordance with an embodiment of the invention is illustrated in FIG. 4. The APPS Application marker segment 400 uses a format identifier 402 that uniquely identifies that the Application marker segment contains metadata describing an image synthesized using light field image data. In a number of embodiments, the identifier is referred to as the “DZ Format Identifier” 402 and is expressed as the zero terminated string “PIDZ0”.

The Application marker segment includes a header 404 indicated as “DZ Header” that provides a description of the metadata contained within the Application marker segment. In the illustrated embodiment, the “DZ Header” 404 includes a DZ Endian field that indicates whether the data in the “DZ Header” is big endian or little endian. The “DZ Header” 404 also includes a “DZ Selection Descriptor”.

An embodiment of a “DZ Selection Descriptor” is illustrated in FIG. 5, which includes four bytes. The first two bytes (i.e. bytes 0 and 1) contain information concerning the metadata describing the encoded image that are present (see FIG. 6) and the manner in which the different pieces of metadata are compressed (see FIG. 7). In the illustrated embodiment, the types of metadata that are supported are a depth map, occluded pixel data, virtual view point data, a missing pixel map, a regular edge map, a silhouette edge map, and/or a confidence map. In other embodiments, any of a variety of metadata describing an encoded image obtained from the light field image data used to synthesize the image can be included in the metadata contained within a JFIF file in accordance with an embodiment of the invention. In many instances, the metadata describing the encoded image can include maps that can be considered to be monochrome images that can be encoded using JPEG encoding. In a number of embodiments, the maps can be compressed using lossless JPEG LS encoding. In several embodiments, the maps can be compressed using lossy JPEG encoding. Utilizing JPEG encoding to compress the maps reduces the size of the maps and enables rendering devices to leverage a JPEG decoder to both decode the image contained within the JFIF file and the maps describing the encoded image. The third byte (i.e. byte 2) of the “DZ Selection Descriptor” indicates the number of sets of metadata describing the encoded image that are contained within the Application marker segment and the fourth byte is reserved. Although specific implementations of the header 404 describing the metadata contained within the Application marker segment are illustrated in FIGS. 4-7, any of a variety of implementations can be utilized to identify the maps describing the synthesized image that are present within the metadata contained within an light field image file as appropriate to the requirements of the application in accordance with embodiments of the invention.

#### Depth Map

Referring back to FIG. 4, the Application marker segment also includes a “Depth Map Header” 406 that describes depth map 416 included within the Application marker segment. The “Depth Map Header” 406 includes an indication 408 of the size of “Depth Map Attributes” 410 included within the “Depth Map Header”, the “Depth Map Attributes” 410, and a “Depth Map Descriptor” 412. As noted above, the depth map 416 can be considered to be a monochrome image and lossless or lossy JPEG encoding can be utilized to compress the “Depth Map Data” included in a JFIF file.

A “Depth Map Attributes” table in accordance with an embodiment of the invention is illustrated in FIG. 8 and includes information concerning the manner in which the depth map should be used to render the encoded image. In the



illustrated embodiment, the information contained within the “Depth Map Attributes” table includes the focal plane and the F# of the synthetic aperture to utilize when rendering the encoded image. Although specific pieces of information related to the manner in which the depth map can be utilized to render the encoded image are illustrated in FIG. 8, any of a variety of pieces of information appropriate to the requirements of a specific application can be utilized in accordance with embodiments of the invention.

A “Depth Map Descriptor” in accordance with an embodiment of the invention is illustrated in FIG. 9 and includes metadata describing the depth map. In the illustrated embodiment, the “Depth Map Descriptor” includes a zero terminated identifier string “PIDZDH0” and version information. In other embodiments, any of a variety of pieces of information appropriate to the specific requirements of particular applications can be utilized in accordance with embodiments of the invention.

A JFIF Application marker segment is restricted to 65,533 bytes. However, an Application marker can be utilized multiple times within a JFIF file. Therefore, depth maps in accordance with many embodiments of the invention can span multiple APPS Application marker segments. The manner in which depth map data is stored within an Application marker segment in a JFIF file in accordance with an embodiment of the invention is illustrated in FIG. 10. In the illustrated embodiment, the depth map data is contained within a descriptor that is uniquely identified using the “PIDZDD0” zero terminated string. The descriptor also includes the length of the descriptor and depth map data.

Although specific implementations of a depth map and header describing a depth map within an Application marker segment of a JFIF file are illustrated in FIGS. 4, 8, 9, and 10, any of a variety of implementations can be utilized to include a depth map describing an encoded image within a JFIF file as appropriate to the requirements of the application in accordance with embodiments of the invention.

#### Occlusion Data

Referring back to FIG. 4, the Application marker segment also includes a “Camera Array Header” 418 that describes occlusion data 428 for individual cameras within an array camera that captured the light field image data utilized to synthesize the image contained within the light field image file. The occlusion data can be useful in a variety of post processing processes including (but not limited) to process that involve modifying the viewpoint of the encoded image. The “Camera Array Header” 418 includes an indication 420 of the size of a “Camera Array General Attributes” table 422 included within the “Camera Array Header”, the “Camera Array General Attributes” table 422, and a “Camera Array Descriptor” 424.

A “Camera Array General Attributes” table in accordance with an embodiment of the invention is illustrated in FIG. 11 and includes information describing the number of cameras and dimensions of a camera array utilized to capture the light field image data utilized to synthesize the image encoded within the JFIF file. In addition, the “Camera Array General Attributes” table can indicate a reference camera position within the array and/or a virtual view position within the array. The “Camera Array General Attributes” table also provides information concerning the number of cameras within the array for which occlusion data is provided within the JFIF file.

A “Camera Array Descriptor” in accordance with an embodiment of the invention is illustrated in FIG. 12 and includes metadata describing the individual camera occlusion data contained within the JFIF file. In the illustrated embodi-

ment, the “Camera Array Descriptor” includes a zero terminated identifier string “PIDZAH0” and version information. In other embodiments, any of a variety of pieces of information appropriate to the specific requirements of particular applications can be utilized in accordance with embodiments of the invention.

In many embodiments, occlusion data is provided on a camera by camera basis. In several embodiments, the occlusion data is included within a JFIF file using an individual camera descriptor and an associated set of occlusion data. An individual camera descriptor that identifies a camera and identifies the number of occluded pixels related to the identified camera described within the JFIF file in accordance with an embodiment of the invention is illustrated in FIG. 13.

In the illustrated embodiment, the descriptor is identified using the “PIDZCD0” zero terminated string. The descriptor also includes a camera number that can be utilized to identify a camera within an array camera that captured light field image data utilized to synthesize the encoded image contained within the JFIF file. In addition, the descriptor includes the number of occluded pixels described in the JFIF file and the length (in bytes) of the data describing the occluded pixels. The manner in which the occluded pixel data can be described in accordance with embodiments of the invention is illustrated in FIG. 14. The same descriptor “PDIZCD0” is used to identify the occluded pixel data and the descriptor also includes the number of pixels of occluded data contained within the segment, the length of the data in bytes and an offset to the next marker in addition to the occluded pixel data.

Due to the restriction on Application marker segments not exceeding 65,533 bytes in data, the additional information enables a rendering device to reconstruct the occluded pixel data across multiple APPS application marker segments within a JFIF file in accordance with embodiments of the invention.

A table describing an occluded pixel that can be inserted within a JFIF file in accordance with an embodiment of the invention is illustrated in FIG. 15. The table includes the depth of the occluded pixel, the pixel color of the occluded pixel and the pixel coordinates. In the illustrated embodiment, the pixel color is illustrated as being in the RGB domain. In other embodiments, the pixel color can be expressed in any domain including the YCbCr domain.

Although specific implementations for storing information describing occluded pixel depth within an Application marker segment of a JFIF file are illustrated in FIGS. 4, 13, 14, and 15, any of a variety of implementations can be utilized to include occluded pixel information within a JFIF file as appropriate to the requirements of the application in accordance with embodiments of the invention.

#### Auxiliary Maps

Referring back to FIG. 4, any of a variety of auxiliary maps can be included in an Application marker segment within a JFIF file in accordance with an embodiment of the invention.

The total number of auxiliary maps and the types of auxiliary maps can be indicated in the Application marker segment. Each auxiliary map can be expressed using an “Auxiliary Map Descriptor” 432 and “Auxiliary Map Data” 434. In the illustrated embodiment, the “Auxiliary Map Descriptor” 432 is included in an “Auxiliary Map Header” 430 within the Application marker segment in the JFIF file.

An “Auxiliary Map Descriptor” that describes an auxiliary map contained within a light field image file in accordance with an embodiment of the invention is illustrated in FIG. 16. The “Auxiliary Map Descriptor” includes an identifier, which is the “PIDZAM0” zero terminated string and information specifying the type of auxiliary map and number of bits per



pixel in the map. As noted above, any of a variety of auxiliary maps derived from light field image data used to synthesize an encoded image can be included within a JFIF file in accordance with embodiments of the invention. In the illustrated embodiment, confidence maps, silhouette edge maps, regular edge maps, and missing pixel maps are supported.

“Auxiliary Map Data” stored in a JFIF file in accordance with an embodiment of the invention is conceptually illustrated in FIG. 17. The “Auxiliary Map Data” uses the same “PDIZAD0” zero terminated string identifier and includes the number of pixels of the auxiliary map contained within the segment, the length of the data in bytes and an offset to the next marker in addition to pixels of the auxiliary map. Due to the restriction on Application marker segments not exceeding 65,533 bytes in data, the additional information enables a rendering device to reconstruct the auxiliary map describing the encoded image across multiple APPS application marker segments within a JFIF file.

Although specific implementations for storing auxiliary maps within an Application marker segment of a JFIF file are illustrated in FIGS. 4, 16, and 17, any of a variety of implementations can be utilized to include auxiliary map information within a JFIF file as appropriate to the requirements of the application in accordance with embodiments of the invention. Various examples of auxiliary maps that can be utilized to provide additional information concerning an encoded image based upon the light field image data utilized to synthesize the encoded image in accordance with embodiments of the invention are discussed below.

#### Confidence Maps

A confidence map can be utilized to provide information concerning the relative reliability of the information at a specific pixel location. In several embodiments, a confidence map is represented as a complimentary one bit per pixel map representing pixels within the encoded image that were visible in only a subset of the images used to synthesize the encoded image. In other embodiments, a confidence map can utilize additional bits of information to express confidence using any of a variety of metrics including (but not limited to) a confidence measure determined during super resolution processing, or the number of images in which the pixel is visible.

#### Edge Maps

A variety of edge maps can be provided included (but not limited to) a regular edge map and a silhouette map. A regular edge map is a map that identifies pixels that are on an edge in the image, where the edge is an intensity discontinuity. A silhouette edge maps is a map that identifies pixels that are on an edge, where the edge involves an intensity discontinuity and a depth discontinuity. In several embodiments, each can be expressed as a separate one bit map or the two maps can be combined as a map including two pixels per map. The bits simply signal the presence of a particular type of edge at a specific location to post processing processes that apply filters including (but not limited to) various edge preserving and/or edge sharpening filters.

#### Missing Pixel Maps

A missing pixel map indicates pixel locations in a synthesized image that do not include a pixel from the light field image data, but instead include an interpolated pixel value. In several embodiments, a missing pixel map can be represented using a complimentary one bit per pixel map. The missing pixel map enables selection of post-processing filters to improve image quality. In many embodiments, a simple interpolation algorithm can be used during the synthesis of a higher resolution from light field image data and the missing pixels map can be utilized to apply a more computationally expensive interpolation process as a post processing process.

In other embodiments, missing pixel maps can be utilized in any of a variety of different post processing process as appropriate to the requirements of a specific application in accordance with embodiments of the invention.

#### Rendering Images Using Light Field Imaging Files

When light field image data is encoded in a light field image file, the light field image file can be shared with a variety of rendering devices including but not limited to cameras, mobile devices, personal computers, tablet computers, network connected televisions, network connected game consoles, network connected media players, and any other device that is connected to the Internet and can be configured to display images. A system for sharing light field image files in accordance with an embodiment of the invention is illustrated in FIG. 18. The system 1800 includes a mobile device 1802 including an array camera configured to capture light field image data and encode the light field image data in a light field image file. The mobile device 1802 also includes a network interface that enables the transfer of a light field image file to other rendering devices via the Internet 1804. In several embodiments, the light field image file is transferred with the assistance of a server system 1806 that can either store the light field image file for access by other devices or relay the light field image file to other rendering devices. In many embodiments, the server system 1806 provides a user interface that enables users to modify the rendering of the image provided to the device. In several embodiments, the server system 1806 provides the light field image file to a device for rendering. In the illustrated embodiment, a variety of network connected rendering devices 1808 are illustrated including a mobile phone and a personal computer. In other embodiments, any of a variety of network connected and/or disconnected devices can render images using a light field image file in accordance with embodiments of the invention. Rendering devices and processes for rendering images in accordance with embodiments of the invention are discussed further below.

#### Rendering Devices

A rendering device in accordance with embodiments of the invention typically includes a processor and a rendering application that enables the rendering of an image based upon a light field image data file. The simplest rendering is for the rendering device to decode the encoded image contained within the light field image data file. More complex renderings involve applying post processing to the encoded image using the metadata contained within the light field image file to perform manipulations including (but not limited to) modifying the viewpoint of the image and/or modifying the focal plane of the image.

A rendering device in accordance with an embodiment of the invention is illustrated in FIG. 19. The rendering device 1900 includes a processor 1902, memory 1904, and an optional network interface 1906. The memory contains a rendering application 1908 that is used to configure the microprocessor to render images for display using a light field image file 1910. In the illustrated embodiment, the light field image file is shown stored in memory. In other embodiments, the light field image file can be stored in an external storage device. Although a specific rendering device is illustrated in FIG. 19, any of a variety of rendering devices can be utilized in accordance with embodiments of the invention including (but not limited to) the types of devices that are customarily used to display images using image files. Processes for rendering of images using light field image files in accordance with embodiments of the invention are discussed further below.



## Processes for Rendering Images Using Light Field Image Files

As noted above, rendering a light field image file can be as simple as decoding an encoded image contained within the light field image file or can involve more complex post processing of the encoded image using metadata derived from the same light field image data used to synthesize the encoded image. A process for rendering a light field image in accordance with an embodiment of the invention is illustrated in FIG. 20. The process 2000 includes parsing (2002) the light field image file to locate the encoded image contained within the image file. The encoded image file is decoded (2004). As noted above, the image can be encoded using a standards based encoder and so the decoding process can utilize a standards based codec within a rendering device, or the image can be encoded using a proprietary encoding and a proprietary decoder is provided on the rendering device to decode the image. When the process for rendering the image simply involves rendering the image, the decoded image can be displayed. When the process for rendering the image includes post processing, the image file is parsed (2006) to locate metadata within the file that can be utilized to perform the post processing. The metadata is decoded (2008). The metadata can often take the form of maps that can be encoded using standards based image encoders and a standards based decoder present on the rendering device can be utilized to decode the metadata. In other embodiments, a proprietary decoding process is utilized to decode the metadata. The metadata can then be used to perform (2010) the post processing of the encoded image and the image can be displayed (2012). The display of the image can be local. Alternatively the image can be streamed to a remote device or encoded as an image and provided to a remote device for display.

Although specific processes for rendering an image from a light field image file are discussed with reference to FIG. 20, any of a variety of processes appropriate to the requirements of a specific application can be utilized to render an image for display using a light field image file in accordance with an embodiment of the invention. As noted above, any of a variety of standards based encoders and decoders can be utilized in the encoding and decoding of light field image files in accordance with embodiments of the invention. Processes for rendering images using light field image files that conform to the JFIF standard and include an image and/or metadata encoded in accordance with the JPEG standard are discussed further below.

## Rendering Images Using JFIF Light Field Image Files

The ability to leverage deployed JPEG decoders can greatly simplify the process of rendering light field images. When a light field image file conforms to the JFIF standard and the image and/or metadata encoded within the light field image file is encoded in accordance with the JPEG standard, a rendering application can leverage an existing implementation of a JPEG decoder to render an image using the light field image file. Similar efficiencies can be obtained where the light field image file includes an image and/or metadata encoded in accordance with another popular standard for image encoding.

A rendering device configured by a rendering application to render an image using a light field image file in accordance with an embodiment of the invention is illustrated in FIG. 21. The rendering device 2100 includes a processor 2102, memory 2104, and an optional network interface 2106 that can be utilized to receive light field image files. In the illustrated embodiment, the memory 2104 of the rendering device 2100 includes a rendering application 2108, a JPEG decoder application 2110, and a light field image file 2112 that con-

tains at least one image and/or metadata encoded in accordance with the JPEG standard. The rendering application 2108 configures the processor to parse the light field image file to locate an encoded image and to decode the encoded image using the JPEG decoder application 2110. Similarly, the rendering application can configure the processor to parse the light field image file to locate metadata and to decode encoded maps contained within the metadata using the JPEG decoder.

Although specific rendering devices including JPEG decoders are discussed above with reference to FIG. 21, any of a variety of rendering devices incorporating standards based decoders can be utilized to render images from appropriately encoded light field image files in accordance with embodiments of the invention. Processes for decoding light field image files that conform with the JFIF standard and that contain at least one image and/or metadata encoded in accordance with the JPEG standard in accordance with embodiments of the invention are discussed further below.

## Processes for Rendering Images from JFIF Light Field Image Files

Processes for rendering images using light field image files that conform to the JFIF standard can utilize markers within the light field image file to identify encoded images and metadata. Headers within the metadata provide information concerning the metadata present in the file and can provide offset information or pointers to the location of additional metadata and/or markers within the file to assist with parsing the file. Once appropriate information is located a standard JPEG decoder implementation can be utilized to decode encoded images and/or maps within the file.

A process for displaying an image rendered using a light field image file that conforms to the JFIF standard using a JPEG decoder in accordance with an embodiment of the invention is illustrated in FIG. 22. The process 2200 involves parsing (2202) the light field image file to locate a Start of Image (SOI) Marker. The SOI marker is used to locate an image file encoded in accordance with the JPEG format. The encoded image can be decoded (2204) using a JPEG decoder. When no post processing of the decoded image is desired, the image can simply be displayed. Where post processing of the image is desired (e.g. to change the view point of the image and/or the focal plane of the image), the process parses (2206) the light field image file to locate an appropriate Application marker. In the illustrated embodiment, an APP9 marker indicates the presence of metadata within the light field image file. The specific metadata within the file can be determined by parsing (2206) a header within the APP9 Application marker segment that describes the metadata within the file. In the illustrated embodiment, the header is the "DZ Header" within the APP9 Application marker segment. The information within the metadata header can be utilized to locate (2208) specific metadata utilized in a post processing process within the light field image file. In instances where the metadata is encoded, the metadata can be decoded. In many embodiments, metadata describing an encoded image within a light field image file is in the form of a map that provides information concerning specific pixels within an encoded image contained within the light field image file and JPEG encoding is used to compress the map. Accordingly, a JPEG decoder can be utilized to decode the map. The decoded metadata can be utilized to perform (2212) a post processes the decoded image. The image can then be displayed (2214). In many embodiments, the image is displayed on a local display. In a number of embodiments, the image is streamed to a remote display or encoded as an image and forwarded to a remote device for display.



Although specific processes for displaying images rendered using light field image files are discussed above with respect to FIG. 22, any of a variety of processes for parsing a light field image file and decoding images and/or metadata encoded in accordance with the JPEG standard using a JPEG decoder can be utilized in accordance with embodiments of the invention. Much of the discussion above references the use of metadata derived from light field image data and contained within a light field image file to perform post processing processes on an encoded image synthesized from the light field image data. Post processing of images synthesized from light field image data using metadata obtained using the light field image data in accordance with embodiments of the invention are discussed further below.

#### Post Processing of Images Using Metadata Derived from Light Field Image Data

Images can be synthesized from light field image data in a variety of ways. Metadata included in light field image files in accordance with embodiments of the invention can enable images to be rendered from a single image synthesized from the light field image data without the need to perform super resolution processing. Advantages of rendering images in this way can include that the process of obtaining the final image is less processor intensive and less data is used to obtain the final image. However, the light field image data provides rich information concerning a captured scene from multiple viewpoints. In many embodiments, a depth map and occluded pixels from the light field image data (i.e. pixels that are not visible from the reference viewpoint of the synthesized image) can be included in a light field image file to provide some of the additional information typically contained within light field image data. The depth map can be utilized to modify the focal plane when rendering an image and/or to apply depth dependent effects to the rendered image. The depth map and the occluded pixels can be utilized to synthesize images from different viewpoints. In several embodiments, additional maps are provided (such as, but not limited to, confidence maps, edge maps, and missing pixel maps) that can be utilized when rendering alternative viewpoints to improve the resulting rendered image. The ability to render images from different viewpoints can be utilized to simply render an image from a different viewpoint. In many embodiments, the ability to render images from different viewpoints can be utilized to generate a stereo pair for 3D viewing. In several embodiments, processes similar to those described in U.S. Provisional Patent Application Ser. No. 61/707,691, entitled "Synthesizing Images From Light Fields Utilizing Virtual Viewpoints" to Jain (the disclosure of which is incorporated herein by reference in its entirety) can be utilized to modify the viewpoint based upon motion of a rendering device to create a motion parallax effect. Processes for rendering images using depth based effects and for rendering images using different viewpoints are discussed further below.

#### Rendering Images Using Depth Based Effects

A variety of depth based effects can be applied to an image synthesized from light field image data in accordance with embodiments of the invention including (but not limited to) applying dynamic refocusing of an image, locally varying the depth of field within an image, selecting multiple in focus areas at different depths, and/or applying one or more depth related blur model. A process for applying depth based effects to an image synthesized from light field image data and contained within a light field image file that includes a depth map in accordance with an embodiment of the invention is illustrated in FIG. 23. The process 2300 includes decoding (2302) an image synthesized from light field image data contained

within a light field image file. In addition, a depth map derived from the light field image data that describes the synthesized image is also decoded (2304) from metadata contained within the light field image file. One or more depth dependent effects can then be applied (2406) to the pixels of the decoded image based upon the depths of the pixels indicated by the depth map. In a number of embodiments, the depth dependent effects are automatically determined by modifying the focal plane, and/or F number (which provides different depths of fields and degree of blur in out-of-focus regions). The image can then be displayed (2308). In many embodiments, the image is displayed on a local display. In a number of embodiments, the image is streamed to a remote display or encoded as an image and forwarded to a remote device for display.

Although specific processes for applying depth dependent effects to an image synthesized from light field image data using a depth map obtained using the light field image data are discussed above with respect to FIG. 23, any of a variety of processes can be utilized for extracting an image and a depth map from a light field image file and for using the depth map to apply one or more depth dependent effects in accordance with embodiments of the invention. Processes for rendering images from different viewpoints to the reference viewpoint of an image contained within a light field image file based upon a depth map and information concerning occluded pixels contained within the light field image file in accordance with embodiments of the invention are discussed further below.

#### Rendering Images Using Different Viewpoints

One of the compelling aspects of computational imaging is the ability to use light field image data to synthesize images from different viewpoints. The ability to synthesize images from different viewpoints creates interesting possibilities including the creation of stereo pairs for 3D applications and the simulation of motion parallax as a user interacts with an image. Light field image files in accordance with many embodiments of the invention can include an image synthesized from light field image data from a reference viewpoint, a depth map for the synthesized image and information concerning pixels from the light field image data that are occluded in the reference viewpoint. A rendering device can use the information concerning the depths of the pixels in the synthesized image and the depths of the occluded images to determine the appropriate shifts to apply to the pixels to shift them to the locations in which they would appear from a different viewpoint. Occluded pixels from the different viewpoint can be identified and locations on the grid of the different viewpoint that are missing pixels can be identified and hole filling can be performed using interpolation of adjacent non-occluded pixels. In many embodiments, the quality of an image rendered from a different viewpoint can be increased by providing additional information in the form of auxiliary maps that can be used to refine the rendering process. In a number of embodiments, auxiliary maps can include confidence maps, edge maps, and missing pixel maps. Each of these maps can provide a rendering process with information concerning how to render an image based on customized preferences provided by a user. In other embodiments, any of a variety of auxiliary information including additional auxiliary maps can be provided as appropriate to the requirements of a specific rendering process.

A process for rendering an image from a different viewpoint using a light field image file containing an image synthesized using light field image data from a reference viewpoint, a depth map describing the depth of the pixels of the synthesized image, and information concerning occluded pixels in accordance with an embodiment of the invention is



21

illustrated in FIG. 24. The process 2400 includes decoding (2402) an image contained within a light field image file, where the image is an image synthesized from light field image data. The process also includes decoding (2404) a depth map from the light field image file, where the depth map was also obtained from the light field image data used to synthesize the encoded image. Information concerning pixels from the light field image data that are occluded in the reference viewpoint is also obtained (2405) from the light field image file, where the information includes the location and depth of the occluded pixels from the reference viewpoint. In many embodiments, auxiliary information, including auxiliary maps that specify additional information concerning the pixels in the encoded image, is also contained within the light field image file and auxiliary information useful in the rendering of an image from a different viewpoint to the reference viewpoint can be extracted and decoded (2408) from the light field image file. Using the depth map and the depths of the occluded pixels, shifts in the location and depths of pixels in the different viewpoint can be determined (2410). Based upon the shifts, occluded pixels can be determined (2414) and the image displayed. Where auxiliary information is available, the auxiliary information can be utilized to adjust (2412) the pixels in the image prior to rendering. In many embodiments, the adjustments are performed prior to identifying occluded pixels and displaying the final image. In a number of embodiments, the adjustments are performed after occluded pixels are identified.

Although specific processes for rendering an image from a different viewpoint using an image synthesized from a reference view point using light field image data, a depth map obtained using the light field image data, and information concerning pixels in the light field image data that are occluded in the reference viewpoint are discussed above with respect to FIG. 24, any of a variety of processes can be utilized for rendering images from different viewpoints using a light field image file as appropriate to the requirements of specific applications in accordance with embodiments of the invention. Processes for rendering images simulating different lens characteristics from in accordance with embodiments of the invention are discussed further below.

While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as an example of one embodiment thereof. Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their equivalents.

What is claimed:

1. A system for encoding light field image data as a light field image file, comprising:  
 a processor; and  
 memory containing an encoding application and light field image data, where the light field image data comprises a plurality of images of a scene captured from different viewpoints;  
 wherein the encoding application directs the processor to:  
 create a depth map that specifies depths for pixels in a reference image in the plurality of images;  
 encode the reference image; and  
 create a light field image file including the encoded image and metadata describing the encoded image, wherein:

22

the light field image file is structured using the Exchangable image file (Exif) format; and  
 the metadata includes the depth map.

2. The system of claim 1, wherein the light field image file conforms to the JFIF standard.

3. The system of claim 1, wherein the encoded image is encoded in accordance with the JPEG standard.

4. The system of claim 1, wherein the metadata is located within an application marker segment within the light field image file.

5. The system of claim 4, wherein the application marker segment is identified using the APP9 marker.

6. The system of claim 4, wherein the application marker segment is identified using an APP1 marker that is used to identify the Exif data.

7. The system of claim 1, wherein the encoding application directs the processor to encode the depth map and the depth map included in the metadata describing the encoded image is the encoded depth map.

8. The system of claim 7, wherein the depth map is losslessly encoded.

9. The system of claim 8, wherein the encoding application directs the processor to decode the depth map using a JPEG decoder.

10. The system of claim 7, wherein the depth map is encoded using lossy compression.

11. The system of claim 1, wherein:  
 encoding the reference image includes creating a confidence map for the depth map, where the confidence map indicates the reliability of the depth value for a pixel in the depth map; and  
 the metadata describing the encoded image in the light field image file includes the confidence map.

12. The system of claim 1, wherein:  
 encoding the reference image involves identifying pixels in the plurality images of the scene that are occluded in a reference viewpoint; and  
 the metadata describing the encoded image in the light field image file includes descriptions of the occluded pixels.

13. The system of claim 12, wherein the descriptions of the occluded pixels includes data selected from the group consisting of colors, locations, and depths of the occluded pixels.

14. The system of claim 1, wherein:  
 the encoding application directs the processor to generate an edge map that indicates pixels in the reference image that lie on a discontinuity; and  
 the metadata describing the encoded image in the light field image file includes the edge map.

15. The system of claim 14, wherein the edge map identifies whether a pixel lies on a discontinuity selected from the group consisting of an intensity and depth discontinuity.

16. The system of claim 1, wherein:  
 the encoding application directs the processor to generate a missing pixel map that indicates pixels in the reference image that do not correspond to a pixel from the plurality images of the scene and that are generated by interpolating pixel values from adjacent pixels in the reference image; and  
 the metadata describing the encoded image in the light field image file includes the missing pixels map.

17. The system of claim 1, wherein the metadata also includes a focal plane.

18. The system of claim 1, wherein the encoding application directs the processor to:  
 select a second reference image from the plurality of images, where the second reference image is distinct

23

from the reference image and the reference image and the second reference image comprise a stereo pair of images;

encode the second reference image; and  
include the second reference image in the encoded light field image file.

19. A method for encoding light field image data as a light field image file, comprising:

obtaining a set of light field image data comprising a plurality of images of a scene captured from different view-points using an encoding system;

creating a depth map that specifies depths for pixels in a reference image in the plurality of images using the encoding device;

encoding the reference image using the encoding device; and

creating a light field image file including the encoded image and metadata describing the encoded image using the encoding device, wherein:

24

the light field image file is structured using the Exchangeable image file (Exif) format; and  
the metadata includes the depth map.

20. A non-transitory machine readable medium containing processor instructions, where execution of the instructions by a processor causes the processor to perform a process comprising:

obtaining a set of light field image data comprising a plurality of images of a scene captured from different view-points;

creating a depth map that specifies depths for pixels in a reference image in the plurality of images;

encoding the reference image; and

creating a light field image file including the encoded image and metadata describing the encoded image, wherein:

the light field image file is structured using the Exchangeable image file (Exif) format; and  
the metadata includes the depth map.

\* \* \* \* \*